ALLOCATION OF INDIVIDUAL HARMONIC EMISSION LIMITS IN ACCORDANCE WITH THE PRINCIPLES OF IEC/TR 61000-3-6

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To my loving family

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SUMMARY

The ultimate objective of this PhD research is to develop practical harmonic allocation methods for medium voltage (MV), high voltage (HV) and extra high voltage (EHV) systems. The distribution automation system (DAS) has been increasingly used by many utilities with the smart grid (SG) technology to improve reliability and efficiency in the operation of distribution systems. Many applications such as fault location identification, peak demand prediction, service restoration, network optimization, reactive-power planning, feeder reconfiguration, state estimation, short-circuit analysis, harmonic analysis etc. are necessary for DAS. Among those functions, a robust and efficient application of harmonic allocations is necessary for power quality (PQ).

Although utilities provide nearly pure sinusoidal voltage, harmonic currents generated by customers cause voltage distortions so that the supply voltage is no longer sinusoidal. The utility is responsible for the overall coordination of harmonic voltage levels under normal operating conditions in accordance with national requirements. Customers are responsible for maintaining their own harmonic emissions at the specified point of evaluation (POE) below the limits specified by the utility.

Allocation of harmonic emissions to MV and HV-EHV customers having the same agreed power and short-circuit power is the key concept of harmonic allocation. The evaluation procedure is designed in such a way that harmonic emissions from all distorting installations do not cause overall system harmonic voltage levels to exceed the planning and compatibility levels.

Both IEC 61000-3-6 [1] and IEEE Std.519 [2] are two types of well-known harmonic allocation standards. Their philosophies in harmonic allocations are quite

different, but they share a common objective to limit actual harmonic voltages on supply systems to levels that will not result in adverse effects on the equipment.

IEEE Std. 519 can be considered as simpler of the two standards, because the allowable current injection levels are pre-calculated, albeit with insufficient investigation for its emission limits. At the expense of simplicity, this dissertation has clearly demonstrated that the current emission limits in IEEE Std.519 have some problems since it is nearly impossible to fully reflect the precarious characteristics of distribution systems into its own emission limits.

IEC 61000-3-6 makes the current limits more system dependant with detailed rationales, and principles related to harmonic allocations are established (basic EMC concepts, emission limits, summation law and global harmonic voltage contribution). Compared to IEEE Std. 519, which contains some hidden assumptions, the principles of IEC 61000-3-6 can be applied to a wide variety of systems and conditions at the expense of becoming increasingly complex.

Although IEC 61000-3-6 has clear rationales, it has not been effectively applied to real systems since it is more a set of constraints than a procedure for determining harmonic allocation. It has been clearly shown that an assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. An additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to real distribution systems with large number of branches and buses.

To overcome those shortcomings, this dissertation provides a practical method to allocate harmonic emission limits in accordance with the principles of IEC 61000-3-6 [1]. The proposed method is developed with the application of the influence coefficient in [1].

This is a new attempt to implement an algorithm for an evaluation of exact harmonic allocations in complex network topologies with wide-ranging resistances and reactances (such as radial, weakly meshed or distributed generation systems without any simplifying assumptions). It is designed on the basis of the direct method, which has a better mathematical relationship between the system state and control variables and the performance (execution time) than the iterative method.

Comparisons are carried out with analytical proofs to analyze the validity of the principles applied to both standards. Although the ultimate goal of harmonic standards is to fairly allocate harmonic emission limits to each customer to keep a specific voltage level in a given system, both standards differently approach the issue of allocating emission limits. Therefore, the solution sets derived from each of these different approaches are not identical. On the surface, it looks as though they complement each other. However, an in-depth analysis shows some significant differences. It is impossible to directly compare both standards, since they are developed based on different methodologies. Therefore, the comparison is carried out with the key question of whether or not both solution sets ultimately arrive at the same conclusion. From the comparisons, this dissertation clearly shows the significant differences, inaccuracies and violation problems between both standards.

Moreover, due to the cost of being simple and universal pre-calculated harmonic current emission limits, IEEE Std. 519 cannot fully consider the precarious nature of distribution systems in its own emission limits. Therefore, the emission limits of IEEE Std. 519 often boost voltage distortions theoretically up to twice beyond planning levels. IEEE Std. 519 takes the simple deterministic method, which often leads to unrealistically high values, especially at high harmonic orders. This dissertation proposes the necessity to apply the stochastic method in IEC 61000-3-6 [1] to IEEE Std. 519, and show the results of IEEE Std. 519 emission limits, based on the stochastic harmonic flow. In addition, three correction factors are developed to compensate for the influences of the following uncertainties of distribution systems on the harmonic current emission limits: the variation of main transformer sizes (referred to as supply capacity here), the number of feeders, and system voltage levels. The feasibility of proposed correction factors is obviously proven, based on a multi-feeder model of distribution systems with the Monte-Carlo method.

IEC 61000-3-6 is composed of two quite different sets of principles for allocating harmonic emission limits in MV and HV-EHV systems, respectively. The ultimate goal of IEC 61000-3-6 for HV-EHV systems is to fairly apportion maximum global contribution limits to considered stations under the consideration of the ratio of the power supply to the total power supply capacity of the system while guaranteeing the planning levels. This dissertation analytically investigates the allocation method of the global contribution in IEC 61000-3-6. From the analysis results, this dissertation clearly proves that the major principles applied to IEC 61000-3-6 have problems that should not be ignored, since the solution set often violates the planning level. To overcome these problems, this dissertation proposes a new method that fairly apportions the global contribution limit to each busbar while guaranteeing the planning levels in HV-EHV systems. The feasibility of the proposed method has been clearly demonstrated by guaranteeing that the worst resulting voltage distortions derived from the proposed method are equal to the given planning level, regardless of system structures and circumstances.

Finally, this dissertation provides a methodology to identify the effects of the background voltage distortion on a particular MV customer under a harmonic compliance test in accordance with the IEC 61000-3-6 principles. IEC 61000-3-6 and IEEE Std. 519 are the harmonic standards that are developed to fairly allocate emission limits to their customers so as not to violate given planning levels without consideration of the background voltage distortion. Therefore, one major difficulty in harmonic standards is how to separate the customer and supply side harmonic contributions from the measured quantity. Customers under compliance tests are often concerned about the effects of background voltage distortions generated by the other customers at the point of evaluation (POE). To solve this problem, separation methods have been proposed from the viewpoint of the measurement side. This dissertation is the first attempt to approach this problem from the viewpoint of harmonic standards. This dissertation clearly proposes a concrete method of separating contributions generated by a particular customer from other customers connected to the supply system, based on IEC 61000-3-6. In addition, this dissertation clearly concludes that the impact of background voltage distortion cannot be ignored, since a considerable non-linear current can be generated in accordance with the level of the load impedance and the background voltage distortion at the POE.

This dissertation strongly supports IEC 61000-3-6 and IEEE Std. 519, and adds to its value. In addition, the findings of this dissertation could help users determine the harmonic contributions of the parties involved more reasonably, accurately and efficiently with the application of distribution automation systems (DAS).

CHAPTER 1

Introduction and Literature Review

1.1 Introduction

Theoretically, the harmonic standards should fulfill two ultimate requirements. First, the planning levels in a given system should be apportioned fairly to each customer proportional to his or her size of contraction. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system. Second, the harmonic standards should insure that the system voltages are inviolable if all customers are in compliance with the standards. Therefore, when the system is fully loaded, and all consumers inject up to their emission limits, the worst voltage distortion should be equal to the planning level theoretically in accordance with its own methodology. Therefore the standards should fulfill these two requirements.

IEC 61000-3-6 and IEEE Std. 519 have by now been accepted as two well known standards for interconnecting the MV and HV-EHV customers to utility systems and widely adopted as standards to many power utilities. The ultimate goal of both standards is to limit the actual harmonic voltages on the supply systems to specific levels, which will not result in adverse effects on equipment by limiting the emission limits to each customer, not to cause unacceptable voltage distortion levels under normal system characteristics.

Even though the ultimate goal of both standards is exactly identical, the solution set of the emission limits is significantly different since the planning levels, the voltage and current emission limits were designed differently.

It is worth noting that the harmonic current emission limits of both standards have not been compared and investigated with analytical proofs because there is still no explanation that discusses the origin of the emission limits in IEEE Std. 519, or the complex feature of IEC 61000-3-6.

The primary objective of this PhD research is to propose the exact harmonic allocation methods according to the principles of IEC 61000-3-6 for the MV and HV-EHV customers and to improve the current emission limits of IEEE Std.519. This dissertation consists of five tasks.

First, for the current emission limits of the MV systems, IEC 61000-3-6 has rationales regarding its own principles and has detailed formula for the emission limits, but it has not been effectively applied since it is more a set of constraints than a procedure for determining harmonic allocation. An assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. This assumption has defeated the excellent features of IEC 61000-3-6 since it leads the solution set to inaccuracy. Additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with a large number of branches and buses in MV systems. To overcome those shortcomings, this dissertation proposes a method with application of the influence coefficient in IEC 61000-3-6, in Task I. The proposed method is a novel attempt to implement an algorithm for evaluation of exact harmonic allocation in complex network topologies with wide-ranging resistances and reactances (such as radial, weakly-meshed or distributed generation systems without any simplifying assumptions). Moreover, the proposed method strongly supports IEC 61000-3-6 and adds to its value, and could help the users to allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently with application of the distribution automation systems (DAS).

Second, many engineers working on power quality (PQ) have been wondering which methodology they follow since both IEC 61000-3-6 and IEEE Std. 519 approach the issue of allocating the emission limits differently, and the solution set derived from both are not identical. IEEE Std. 519 can be considered as the simplest standard because the allowable emission limits are pre-calculated, but there is no rationale concerning its emission limits in its page. The major goal of Task II is to compare and investigate the conventional harmonic allocation methodologies of both standards for the MV customers to analyze the weak and strong points of both standards. On the surface, they complement each other. However, an in-depth analysis has shown some significant differences. It is impossible to directly compare both standards since they were developed based on the different methodologies. Comparisons have been performed with the key question of whether or not both solution sets ultimately arrive at the same conclusion. Investigation has been carried out with the primary goal of whether the harmonic guidelines of the standards make the systems inviolable if all customers are in compliance with the guidelines. From the results of the comparison and investigation, this dissertation has clearly shown a significant difference, inconsistency and inaccuracy in both standards.

Third, IEEE Std. 519 takes the simple deterministic method, which often leads to unrealistically high values, especially at high harmonic orders. Moreover, due to the cost of being simple and universal pre-calculated harmonic current emission limits, IEEE Std. 519 cannot fully consider the precarious nature of distribution systems in its own emission limits. Therefore, the emission limits of IEEE Std. 519 often boost voltage distortions theoretically up to twice beyond planning levels. This dissertation proposes the necessity to apply the stochastic method in IEC 61000-3-6 [1] to IEEE Std. 519, and show the results of IEEE Std. 519 emission limits, based on the stochastic harmonic flow. In addition, three correction factors are developed to compensate for the influences of the following uncertainties of distribution systems on the harmonic current emission limits: the variation of the main transformer size (referred to as supply capacity here), the number of feeders, and system voltage levels. Task III presents correction factors to improve the harmonic current emission limits of IEEE Std. 519 [2] in MV systems. The feasibility of the correction factors proposed is obviously proven, based on a multi-feeder model of distribution systems with the Monte-Carlo method.

Fourth, for the current emission limits of the HV-EHV systems, this dissertation has clearly proved that the allocation principle in IEC 61000-3-6 has some hidden problems that should not be ignored, which are due to invalid applications of the influence coefficient. These problems associated with the major principle are investigated based on the case studies and numerical proofs. To overcome these hurdles, in Task IV, a method is presented for sharing the common HV-EHV planning levels between the different substations or busbars in the supply system (referred to as a global contribution) in accordance with the principles of IEC 61000-3-6[1]. The feasibility of the proposed method has been clearly demonstrated by guaranteeing that the worst resulting voltage distortions derived from the proposed method are equal to the given planning level, regardless of system structures and circumstances. Task V provides a methodology to identify the effects of the background voltage distortion on a particular MV customer under a harmonic compliance test in accordance with the IEC 61000-3-6 principles.

IEC 61000-3-6 and IEEE Std. 519 are the harmonic standards that are developed to fairly allocate emission limits to their customers so as not to violate given planning levels without consideration of the background voltage distortion. Therefore, one major difficulty in harmonic standards is how to separate the customer and supply side harmonic contributions from the measured quantity. Customers under compliance tests are often concerned about the effects of background voltage distortions generated by the other customers at the point of evaluation (POE). To solve this problem, separation methods have been proposed from the viewpoint of the measurement side. This dissertation is the first attempt to approach this problem from the viewpoint of harmonic standards. This dissertation clearly proposes a concrete method of separating contributions generated by a particular customer from other customers connected to the supply system, based on IEC 61000-3-6.

In addition, this dissertation clearly concludes that the impact of background voltage distortion cannot be ignored, since a considerable non-linear current can be generated in accordance with the level of the load impedance and the background voltage distortion at the POE.

1.2 Scope

The entire research consists of five tasks :

- Task I
    - Demonstrating the vulnerabilities and inaccuracies in the existing methods of allocating the current emission limits to the MV customers in IEC 61000-3-6.

- Developing more accurate methods to overcome the hurdles in the allocation methods of IEC 61000-3-6 for the MV customers.

- Task II
    - Assessing, comparing and contrasting the harmonic allocation methodologies of both IEC 61000-3-6 and IEEE Std. 519 in the MV systems.
- Task III
    - Demonstrating the vulnerabilities and inaccuracies in the existing methods of allocating the current emission limits to the MV customers in IEEE Std. 519.
    - Developing correction factors to improve the harmonic current emission limits of IEEE Std. 519 in MV systems.
- Task IV
    - Identifying the issues of sharing harmonic planning levels and allocating emission limits in IEC 61000-3-6 to the HV-EHV customers.
    - Proposing more accurate methods to correct the allocation methods of IEC 61000-3-6 for the HV-EHV customers.
- Task V
    - Providing a methodology to identify the effects of the background voltage distortion on a particular MV customer under a harmonic compliance test in accordance with the IEC 61000-3-6 principles.
    - Proposing a new method of harmonic flow, based on the general summation law, without any simplifying assumption, to calculate the

background voltage distortions in a given system by injecting the set of harmonic current emission limits evaluated by IEC 61000-3-6.

This dissertation is organized in seven chapters. Chapters 1 is an introductory. Chapters 2, 3, 4, 5 and 6 present Task I, II, III, IV and V, respectively. Chapter 7 is regarding conclusions and contributions.

1.3 Problem Statements

In 1995, an incentive-based scheme proposed was to charge harmonic generators an amount commensurate with their harmonic pollution levels when the limits are exceeded [3]. This was inspired by the well-known power factor management practice. Since the publication of [3], many research efforts have been directed to implement the incentive-based concept [4-7].

A power-direction method for identifying a dominant harmonic source was developed based on finding the direction where harmonic real power flows [8, 9]. This method had been used widely to identify the location of harmonic sources in power systems. However, this method [8, 9] has been discredited [10]. An analogy with a real power flow at the fundamental frequency suggests why this method is unsuitable: the well-known power-angle approximation shows that the direction where power flows through a line is controlled primarily by the phase angle, and not by the magnitude, of the voltages on opposite sides of a line. Therefore, the supposition that harmonic voltage magnitudes should indicate the direction of harmonic power flow across a PCC is inconsistent with the situation at the fundamental frequency[11]. [11] postulated that a reactive power flow may be more suitable.

Techniques involving the representation of customer installation by an equivalent linear circuit have been developed. Such techniques [12] [13] examine the extent to which installation deviates from the behavior expected of an equivalent resistor-inductor combination. Both cases are not particularly constructive since the effect of capacitance is neglected completely in the equivalent circuit.

When utilities assess compliance with a customer's installation, the main difficulty in implementation is how to separate the customer and supply side harmonic contributions from the measured quantity because of background distortion effects.

A pioneering concept of the separation was developed based on the conforming and non-conforming concept [5, 14]. The conforming and non-conforming current methods are noted by [15] to be essentially futile in that the two current components are not orthogonal, and therefore it cannot be uniquely separated [15].

The concept of a harmful and useful (friendly) harmonic current was proposed in [16, 17] depending on the direction of change observed in the harmonic voltage at the PCC after the distorting load is connected. If the injection of harmonic currents at a certain point causes a decrease of harmonic voltages at all other points, it is a useful harmonic current. The Norton approach was presented for modeling distribution networks where the system configuration is not fully known [18]. New power quality indexes [13] were developed by applying the separation concept [5, 14]. Recently intelligent methods have been developed to separate the influence of background voltages from the measured data between the customers and supply systems [19-21].

Above all, to implement the incentive-based scheme, a reasonable allocation method of harmonic emission limits should be developed under the consideration of the customer's size and location. IEC 61000-3-6 and IEEE Std. 519 have by now been accepted as standards for allocating harmonic current emission limits. Although both standards provide guidelines for allocating harmonic emission limits, disputes may arise regarding the accuracy and fairness of the solutions since the solution set derived from both standards are not identical.

1.3.1 IEC 61000-3-6 for MV systems

For current emission limits of MV systems, IEC 61000-3-6 has rationales regarding its own principles and has detailed formulas for the emission limits. However, it has not been effectively applied since it is more a set of constraints than a procedure for determining harmonic allocation. An assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. This assumption has defeated the excellent features of IEC 61000-3-6. An additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with a large number of branches and buses in MV system. Although [1, 22, 23] have been developed to evaluate harmonic current emission limits, all of these methods could not alleviate the need for simplifying assumptions (such as an identical network or loads and uniformly distributed loads).

1.3.2 IEEE Std.519 for MV systems

For over the past two decades, IEEE Std.519 [1] has been applied as a harmonic guideline, along with IEC 61000-3-6 [2]. On the surface, they complement each other [24]. However, an in-depth analysis has shown some significant differences [25]. Many engineers working on power quality (PQ) have wondered which methodology they should follow since both standards approach the issue of allocating the emission limits differently, and the solution set derived from both are not identical. It is necessary to compare and investigate the conventional harmonic allocation methodologies of both [1] and [2]. Although a group leader of IEEE Std. 519 said “The standard should stand by itself, on its own merits, with engineering proof within its pages to show it has been properly thought out with measurable benefits to those who use its guidance [26]”, there is still no explanation discussing the origin of the emission limits in its pages. An excellent feature of the emission limits on IEEE Std. 519 is that they are pre-calculated with several categories instead of specific complicated formulas. At the expense of simplicity, it is difficult to insure for IEEE Std.519 the accuracy of solutions. Moreover, the emission limits were designed without full consideration of all system uncertainties. This is why the standard follows the “first come, first serve” rule. Additionally, it is notable that the current emission limits have originated from the probabilistic concept. However, resulting voltage distortions are evaluated based on the deterministic method [27]. This leads the standard to be inconsistent by theoretically causing voltage violations. Note that no research can be found on comparing or investigating for both standards with analytical proofs. Rather, only limited studies have summarized both standards [24, 25].

1.3.3 IEC 61000-3-6 for HV-EHV systems

The significant feature of consumers connected to HV-EHV systems is the limited number and large size of the agreed power compared to customers connected to MV systems. Therefore, utilities try to assess compliance with HV-EHV customers more carefully than with MV customers since their influence is higher on the power systems. IEC 61000-3-6 [1] has also been known as a harmonic guideline for HV-EHV systems.

However, the allocation methodology for emission limits has not been investigated, and it is difficult to apply to real systems compared to its fame because of the vagueness of the major principle, which is referred to as an influence coefficient. The influence coefficient is the stepping stone for allocating current emission limits of HV-EHV systems. Note that no research can be found on the investigation of the emission limits for the HV-EHV systems in [1].

This methodology applied to IEC 61000-3-6 reveals two severe problems. One is the equation, which states that when all individual users are injecting up to their emission limits, the summation of all global contributions based on the summation exponents for harmonics should be equal to or less than the planning levels, taking into account the influence coefficients. This supposition is valid only when a network topology is simple without any lateral or meshed structure. The meshed systems would need a more general or advanced approach to share the harmonic planning levels. The other one is the equations deriving the solution set of the maximum acceptable global contribution at each busbar since the application of the influence coefficients is not applied appropriately. From these two problems, the value of the worst voltage distortion, which is evaluated by injecting the current emission limits obtained from the solution set of the global contributions, is lower or higher than the harmonic planning levels.

1.4 Background Information

The harmonic standards are classified into three types such as HV-EHV, MV, and low voltage (LV) systems according to nominal voltage levels. Regarding harmonic emission limits in LV system levels, widely accepted international standards such as IEC

61000-3-2 [28], IEC 61000-3-4 [29], and IEC 61000-3-12 [30] have been well enforced with the concept of reference impedance in IEC 60725 [31].

IEC 61000-3-2 is applicable to electrical and electronic equipment with input current less than or equal to 16A per phase. There are four classes of equipment limited in this standard. Each class defines the maximum permissible harmonic current for individual harmonic order up to the 40^{th} harmonic order. IEC 61000-3-4 categorizes the equipment more than 16A into three main stages. This standard not only deals with individual equipment but also sets limits for whole system installation. Both single phase and three-phase harmonic limits are addressed. This standard also gives consideration to short circuit ratio. IEC 61000-3-12 deals with the limitation of harmonic currents injected into the public supply system. The limits given in this International Standard are applicable to electrical and electronic equipment with a rated input current exceeding 16A and up to and including 75A per phase. IEEE Std. 519 sets the limits of harmonic voltage and current at the point of evaluation. The philosophy behind this standard is to prevent harmonic current from traveling back to the power system and affecting other customers.

For HV-EHV and MV systems, only a number of countries have their own regulatory standards to control the voltage distortion levels in distribution systems. Examples of such specifications include the British recommendation G5/4-1 [32] and the Australian standard [22]. Some Canadian utilities adopted IEEE Std. 519 [2] as their harmonic requirements [33]. Generally, they have started applying similar harmonic allocation methodologies and recommended limits based on conventional international standards such as [1] and [2]. [2] restricts current emission limits according to the short circuit levels at the point of evaluation and the size of customers. It has been found by [24] that most “utility versions” of the standard required customers to comply with voltage limits, and customers may be disconnected if the cause excessive voltages even when their current emission limits are within specification of the limits. The approach of [1] differs from [2] in that it considers the total system power supply capacity in the allocation of the emission limits. [1] provides formulas to estimate the allowed emission limits for each customer and to share the system harmonic absorption capability [24].

1.4.1 IEC 61000-3-6

Regarding IEC 61000-3-6 [1], a large amount of space is dedicated to the description of how to allocate the emission limits to all customers connected to a supply system with a probabilistic method. The main procedures for the allocation of emission limits consist of three following steps: a) planning levels, b) individual voltage emission limits, and c) individual current emission limits. In each step, specific formulas are designed to insure two requirements: a) planning levels should be apportioned fairly to each customer proportional to his or her size of contraction (Fairness), and b) harmonic standards should insure the voltage planning levels (Consistency).

To derive the harmonic current emission limits based on the two requirements, the formulas in [1] consider the influence of all system uncertainties on the voltage distortions such as network topologies, stochastic nature of harmonics, the location of customers, the number of customers, the agreed power, the power supply capability, the number of feeders, and system voltage levels.

Equation (1.1) is simplifying formulas for evaluating the harmonic current emission limits (E_{Ihi}) applied to IEC 61000-3-6. More detailed information can be found in [1]. The harmonic current allocated to a MV installation with maximum demand S_i connected at a point where the supply harmonic reactance is x_h is taken as:

$$E_{Ihi} = \frac{A_{hMV} S_i^{(1/\alpha)}}{\sqrt{x_h}} \tag{1.1}$$

where A_{hMV} and α is the allocation constant and an exponent for MV systems, respectively.

The allocation constant A_{hMV} needs to be calculated for each MV subsystem using the condition that the highest harmonic voltage in the subsystem is not to exceed the planning level. The highest harmonic voltage is assumed to be at the remote end of the feeder which has the worst voltage regulation. In the absence of precise data, this feeder can be taken as the one for which the product of supply capability and length is the largest. Before making detailed MV calculations, it is necessary to estimate the contribution of LV loads to MV harmonic voltages. It is assumed that an LV load S_{LV} gives a harmonic current:

$$I_{hLV} = A_{hLV} \cdot \sqrt[\alpha]{S_{LV}} \tag{1.2}$$

where A_{hMV} is the allocation constant for LV systems.

A_{hLV} varies with harmonic order and may differ from country to country (or even from region to region) depending on the penetration of electronic loads and their usage pattern. It can be estimated from the measurement of the harmonic current for a representative feeder supplying a known load. Where there is a large difference in the fault level between LV and MV systems (for example where LV feeders are overhead lines of a hundred or more meters in length), and the voltage in LV systems is known to be acceptable, the MV voltage caused by LV loads is a fraction of that in LV systems. This condition also applies to situations where the total power of distorting loads connected at LV is relatively low compared to MV distorting loads.

Steps in the allocation procedure are followings.

(a) For each feeder in the subsystem determine R, defined as the ratio of sending end to receiving end fault level;

(b) Define Rw as the value of R for the weakest feeder. Determine Ra, the average R for the remaining feeders. If there is a wide range in the values of R for these feeders, a value should be obtained weighted according to the load capability of each feeder. Similarly this dissertation defines S_{LVW} as the LV load connected to the weakest feeder and S_{LVn} as the LV load connected to the n remaining feeders;

(c) Estimate the harmonic voltage caused by LV loads at the MV level from:

$$V_{hLV} = A_{hLV}\ x_h \sqrt[\alpha]{S_{LVw} R_w^{\ 0,7\alpha} + S_{LVn}} \tag{1.3}$$

where x_h is the harmonic reactance at the equivalent supply busbar.

(d) Determine the harmonic voltage allowance (G_{hMV}) available to all MV loads in the subsystem

$$G_{hMV} = \sqrt[\alpha]{L_{hMV}^{\ \alpha} - L_{hUS}^{\ \alpha} - V_{hLV}^{\ \alpha}} \tag{1.4}$$

(e) Determine the allocation constant for all MV loads in the subsystem, noting carefully that the denominator of next equation contains a square root as well as a root.

$$A_{hMV} = \frac{G_{hMV}}{\sqrt{x_h}\sqrt[\alpha]{S_{MVw} R_w^{0,33\,\alpha} + S_{MVn} R_a^{-0,3\,\alpha}}} \tag{1.5}$$

(f) Determine the harmonic current allocation for a particular consumer using Equation (1.1) above.

Although [1] has been known to be a complicated standard with a wide consideration of the system conditions, it can not provide the exact method to derive the solution set of emission limits in accordance with its own principles since a simplifying method has been applied under the assumption of a uniform distribution of installations to avoid complex calculation. In addition, the method presented in [1] does not fully consider the network topology so that it is impossible to apply the allocation method to the complicated network topology such as the meshed and DG systems. This is why engineers tend to avoid applying this standard to their systems. The adoption of the simplifying assumption might be due to a lack of tools for the harmonic analysis based on the probabilistic concept several decades ago. However, the situation has changed significantly since then. A method to overcome those hurdles is needed to improve PQ in power systems.

1.4.2 Concept of Summation Law

When many customers producing harmonic currents are present in the same distribution system, the harmonic current in the lines and the harmonic voltage at the point of evaluation (POE) depends on the superposition effect caused by different amplitudes and phase angles of the currents emitted from different sources. An exact evaluation of resulting harmonic voltages (vectorial sum) is restricted to a few special cases. Taking the algebraic sum of the contributions by each harmonic source may represent the worst case, but this method often leads to unrealistically high values, especially at high harmonic orders. IEC 61000-3-6 treats harmonics as stochastic quantities. This contrasts with the present version of IEEE Std. 519 in which harmonics are considered as deterministic [27]. Therefore, the summation problem arises when studying the connection of a new customer load producing harmonics. The lack of information, and the inherent variability concerning all of the individual loads, which generate harmonics, leads to the necessity of using a statistical approach for evaluating resulting harmonic vectors. In such an approach, each harmonic source is represented by a randomly time-varying vector. Both the magnitude and phase angle of these vectors are modeled by means of distribution laws. The stochastic treatment has two distinctive advantages over a deterministic approach. Firstly, it allows time and phase diversity between harmonic sources to be accounted for in a relatively simple manner by representing harmonic voltages and currents as 95% non-exceeding quantities. Secondly, the stochastic treatments eliminate the need for the phase angle of harmonic voltage and current sources.

One of the key principles of this stochastic approach is use of summation laws to simplify calculations of the net harmonic current from the distorting loads. Two methods for evaluating the summation of a number of harmonic sources are proposed in [34]. The first summation law, which is based on the factors that depend on load types, can be used for special groups of equipment. The second method was developed based on the Monte-Carlo approach considering that the compatibility level has to be met with a probability of 95% or better [35]. The second summation law is more general and combines the harmonic contributions from the non-linear loads; thus, it is considered as more applicable in most circumstances since it does not consider the load types. The second general method was adopted in [1]. This summation law relies on the power law to incorporate the diversity of the loads allowing frequency domain studies to predict the cumulative probability levels of time varying harmonics. More detailed explanations of the general method can be found in Chapter 2.

1.4.3 Power Flow for Distribution Systems

Some well-known characteristics of distribution systems are a radial or weakly meshed structure; a multiphase and unbalanced operation; an unbalanced distributed load; an extremely large number of branches and nodes; and wide-ranging resistance and reactance values. Those features cause the traditional load flow methods used in HV-EHV systems such as the Gauss-Seidel and Newton-Raphson techniques, to fail to meet the requirements in both the performance and robustness aspects in the distribution system applications [36]. In particular, the assumptions necessary for the simplifications used in the standard fast-decoupled Newton-Raphson method [37] are often not valid in distribution systems [36]. To qualify for a good distribution load flow algorithm, all of the aforementioned characteristics need to be considered. Several load flow algorithms specially designed for distribution systems have been proposed in the literature [38-46]. Some of these methods were developed based on the general topology with strongly meshed systems [38-42]. From those methods, the Gauss implicit-matrix method [40] is one of the most commonly used ones. Recent researches have proposed two representative methods such as the forward/backward and the direct method, which are robust and time-efficient [43-46].

Forward/Backward Technique

The forward/backward sweep technique in [43] is the most powerful method in solving the distribution power flow since it can fully use the topology characteristic of distribution systems. It means that the time-consuming LU decomposition and the forward/backward substitution of the Jacobian matrix or the admittance matrix, required in the traditional Newton Raphson and Gauss implicit matrix algorithms, are not necessary in the new envelopment. One more significant feature of this method is that it is flexible to implement in distribution systems such as the model of dispersed generations (PV nodes), unbalanced and distributed loads, and voltage regulators and shunt capacitors with automatic local tap controls. However, this method needs a compensation-based technique in the case of meshed systems. The extension of the method, which is emphasized in modeling unbalanced loads and dispersed generators, was proposed in [47].

Direct Method

The direct method with the system impedance matrix is also a good method in solving the distribution load flow since the direct mathematical relationship between the system status, and control variables can be found [36, 38, 48]. Traditionally, the network relationship can be represented by an admittance or impedance matrix. Although the work to construct an impedance matrix is much greater than the admittance matrix, the information contents in the impedance matrix are much more than in the admittance matrix [47]. The time-consuming LU decomposition, and the forward/backward substitution of the Jacobian matrix or admittance matrix required in the traditional load flow methods are no longer necessary. Two representative matrices and a simple matrix multiplication are utilized to obtain the system impedance matrix. Test results demonstrate the feasibility and validity of the impedance matrix technique [36].

1.4.4 Harmonic Flow

Harmonic flow can be used to quantify the harmonic distortion in the voltage and current waveforms at various nodes and to determine whether the dangerous resonant problem exists, and how they might be mitigated. Such an analysis has become more important since the presence of harmonic-producing equipment is increasing [49-52]. The commonly used harmonic analysis algorithms can be divided into two categories. The first category is based on the transient-state analysis techniques, such as the time-domain analysis and Wavelet analysis, etc. [53-55]. The second category is the steady-state analysis [56-58]. The steady-state algorithms are developed based on power flow programs and employ frequency-based component models. The steady-state-based algorithms adopted in this dissertation, are more efficient than the transient-state-based algorithms since they are the better choice for large-scale distribution system analysis because of computational economy. This is why the steady-state algorithm has been applied to [1, 2]. The steady-state analysis is broadly classified as: a) the current injection methods [38, 48], and b) the harmonic power flow methods [59, 60].

CHAPTER 2

Allocation of Individual Harmonic Emission Limits to MV Customers in Accordance with the Principles of IEC 61000-3-6

The objective of this chapter is to provide a practical method to allocate harmonic emission limits in accordance with the principles of IEC 61000-3-6 [1]. IEC 61000-3-6 has been applied as a well-known harmonic standard with clear rationales. Moreover, IEC 61000-3-6 presents a simple method with a simplifying assumption for allocating harmonic current emission limits to MV systems. Although this simple method has contributed to calculating emission limits with handwritten calculations, an assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. An additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with a large number of branches and meshed systems.

To improve those shortcomings, the proposed method has been developed with the application of the influence coefficient in [1]. This is a new attempt to implement an algorithm for an evaluation of exact harmonic allocations in complex network topologies with wide-ranging resistances and reactances (such as radial, weakly meshed or distributed generation systems without any simplifying assumptions).

2.1 Introduction

Recently, distribution automation systems (DAS) have been increasingly used by many utilities as smart grid (SG) technology to improve reliability and efficiency in the operation of distribution systems. Many applications, such as fault location identification, peak demand prediction, service restoration, network optimization, reactive-power planning, feeder reconfiguration, state estimation, short-circuit analysis, harmonic analysis, etc. are necessary to construct DAS effectively. Among those applications, a robust and efficient harmonic allocation program is very important for higher power quality (PQ). Although utilities provide nearly pure sinusoidal voltage, a harmonic current generated by customers causes voltage distortion so that the supply voltage is no longer sinusoidal.

The utility is responsible for the overall coordination of harmonic levels under normal operating conditions in accordance with national requirements. The customers are responsible for maintaining their own harmonic emissions at the specified point of evaluation (POE) below the limits specified by the utility. The allocation of equal harmonic emission rights to MV customers having the same agreed upon and short circuit power is the key concept of harmonic allocation principles. Note that only limited research can be found on harmonic emission limits [1, 2, 22, 61-68]. The evaluation procedure is designed in such a way that harmonic emissions from all distorting installations do not cause overall system harmonic voltage levels to exceed the planning and compatibility levels.

There are two types of well-known harmonic allocation standards [1] [2]. Their philosophies in harmonic allocation are quite different, but share a common objective to limit actual harmonic voltages on a supply system to levels that will not result in adverse effects on the equipment.

IEEE 519 [2] can be considered as simpler of the two standards because the allowable current injection levels are pre-calculated, albeit with insufficient justification for its emission limits. An inconsistency permits the allowed current limits to boost voltage distortion limits beyond an acceptable threshold theoretically, as we will show in section 2.3 of this chapter. IEC 61000-3-6 [1] makes the current limits more system dependant with detailed rationales, and detailed principles related to harmonic allocation are established (basic EMC concepts, emission limits, the summation law and global harmonic voltage contribution.)

Compared to IEEE 519, which contains some hidden assumptions, the principles of IEC 61000-3-6 can be applied to wide varieties of systems and conditions at the expense of becoming increasingly complex. In this chapter, this dissertation only focuses on IEC 61000-3-6 [1] in MV systems.

Although [1], [61] have been developed to evaluate harmonic allocations based on the method in [22], all of these methods cannot alleviate the need for simplifying assumptions (such as a simple network and uniformly distributed loads.) In this chapter, this dissertation proposes a new approach for the harmonic current allocation method, which completely adheres to the principles in [1] with the application of the influence coefficient in [1].

This chapter is organized in four sections. Section 2.1 provides the introduction. Section 2.2 describes the algorithm development, while Section 2.3 shows several application results using the proposed method. Conclusions are drawn in Section 2.4.

2.2 Proposed Method

The basic principles of [1] applied to the proposed method such as basic EMC concepts related to harmonic distortion, general principles for emission limits, general summation law and sharing method of global harmonic voltage contribution. More detailed explanations of these essential concepts can be found in [1]. The harmonic allocation method, which has an objective to allocate the individual harmonic current emission limits for each customer, is proposed here. It is based on several new concepts, such as a reference harmonic voltage response set, a reference harmonic current injection set, the worst harmonic voltage distortion and an allocation constant for determining the individual harmonic current emission limits. In this section, this dissertation focuses on the steps in derivation of the individual harmonic current emission limits shown in Figure 2.1.

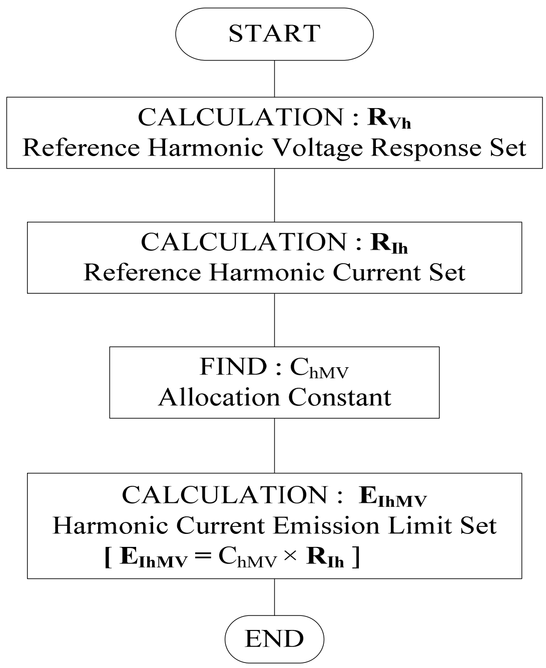


Figure 2.1 : Steps for evaluation of harmonic current emission limit set

2.2.1 Basic Concepts

To evaluate the harmonic current emission limits, two factors should be considered in accordance with [1]. One is consumer’s agreed on power capacity since all customers have the right to inject their full harmonic disturbance into the supply system.

All customers having equal maximum demand have the right to receive equal harmonic voltage emission limits. The other influential factor is the short-circuit power, which depends on the distance from the source to the point of evaluation.

Harmonic Voltage Analysis

A case-study system is shown in Figure 2.2, where it is assumed that Bus 6 on Feeder 1 is the weakest point of the system.

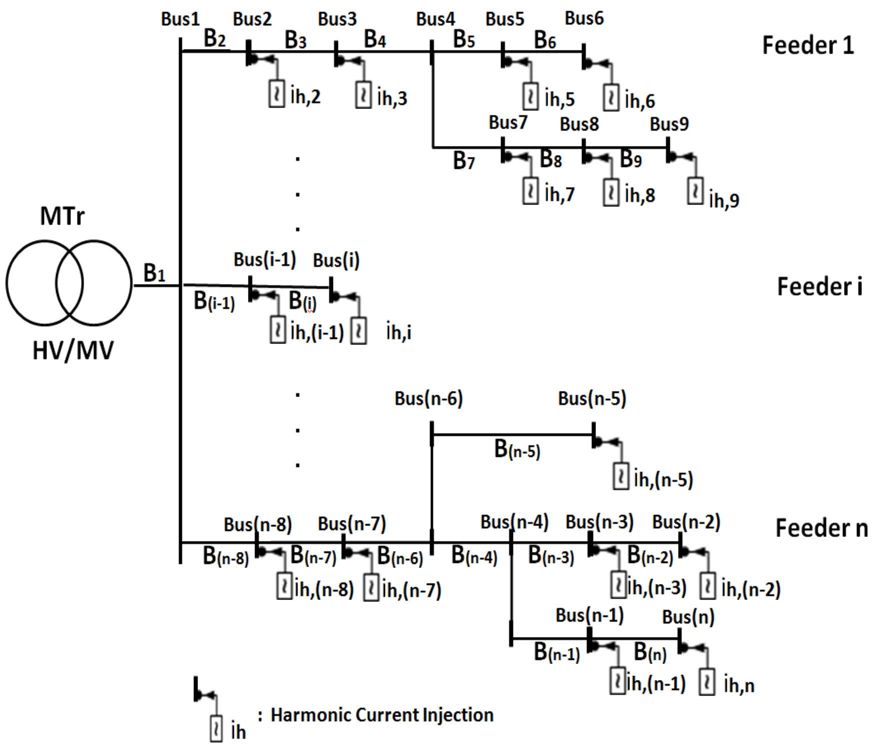


Figure 2.2 : A case-study distribution system

The commonly used harmonic analysis methods can be divided into two categories: 1) Transient-state analysis techniques, such as time domain analysis and 2) Steady-state analysis techniques, broadly classified as: a) the current injection methods, and b) the harmonic power flow methods. Two representative types of power flow techniques that could effectively deal with the features of distribution systems have already been developed in [36, 43]. One of these algorithms is based on the iterative method that is featured by the compensation method with breakpoint impedance matrix [69]. The other is based on a direct method via two representative matrices providing a novel mathematical model for determination of relations between bus voltages, branch currents and bus current injection [36]. By comparing these two methods, the method described in [36] is able to take the maximum advantage of the unique characteristic of the proposed harmonic allocation method since it has better characteristics to apply the summation law. Then, this dissertation does not need to calculate the time consuming compensation-based technique in the meshed system. Moreover, some specific treatment is not necessary to converge the solution set under the shunt capacitors absorbing the harmonic current like [70]. The direct method was therefore used for building the harmonic impedance matrix. The capacitance of the line impedance is usually omitted in the distribution system analysis because of its small effect; therefore, it is not considered in the following derivation. Nevertheless, the capacitance can also be considered in the proposed method if necessary. The proposed algorithm can be expanded to a multiphase line section or bus. To avoid complexity and simplify the explanation of the proposed process, only the 5^{th} harmonic is considered. The method is based on the following assumptions:

- Power system consists of linear devices
- Linear model (inductive reactance is proportional to frequency and capacitive reactance is inversely proportional to frequency).

To analyze the propagation of harmonic currents in Figure 2.2, at harmonic order h, the resulting voltages can be obtained with the system impedance matrix. Traditionally, the network relationship can be represented by an admittance or impedance matrix. Although the work to construct an impedance matrix is much greater than the admittance matrix, the useful readily available information contained in the impedance matrix is much more than in the admittance matrix. It is not necessary to invert the admittance matrix to obtain the impedance matrix. Moreover, the driving point impedance according to harmonic order, a symmetrical fault analysis as well as the stochastic harmonic analysis can be evaluated based on the impedance matrix built with the application of the direct impedance determination method.

$$[\mathbf{V_h}] = [\mathbf{Y_h}]^{-1} \cdot [\mathbf{I_h}] = [\mathbf{Z_h}] \cdot [\mathbf{I_h}] \tag{2.1}$$

where $[\mathbf{V_h}]$ is the unknown harmonic voltage vector, $[\mathbf{Z_h}]$ is the harmonic impedance matrix, and $[\mathbf{I_h}]$ is the harmonic current vector.

For a system with N nodes, the expanded form of (2.1) is expressed as

$$\begin{bmatrix} V_{h,1} \\ V_{h,2} \\ \vdots \\ V_{h,n} \end{bmatrix} = \begin{bmatrix} Z_{h,11} & Z_{h,12} & \cdots & Z_{h,1n} \\ Z_{h,21} & Z_{h,22} & \cdots & Z_{h,2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{h,n1} & Z_{h,n2} & \cdots & Z_{h,nn} \end{bmatrix} \begin{bmatrix} I_{h,1} \\ I_{h,2} \\ \vdots \\ I_{h,n} \end{bmatrix} \tag{2.2}$$

Equation (2.2) shows that the voltages are the results of the different harmonic currents participating based on superposition principle.

Harmonic Voltage Emission Limit

Unlike the resulting voltages, the definition of the harmonic voltage emission limit (E_{Vh}) in [1] are the results of excluding the impacts of all harmonic current excitations except self node. After extracting all the other impact of the currents except self node, the voltage emission limit can be obtained as

$$\begin{aligned}[\mathbf{E_{Vh}}] &= [\mathbf{V_h}] - [[\mathbf{Z_h}] - \mathbf{Dg}([\mathbf{Z_h}])] \cdot [\mathbf{I_h}] \\ &= \mathbf{Dg}([\mathbf{Z_h}])[\mathbf{I_h}]\end{aligned} \tag{2.3a}$$

$$\begin{bmatrix} E_{Vh,1} \\ E_{Vh,2} \\ \vdots \\ E_{Vh,n} \end{bmatrix} = \begin{bmatrix} Z_{h,11} & 0 & \cdots & 0 \\ 0 & Z_{h,22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_{h,nn} \end{bmatrix} \begin{bmatrix} I_{h,1} \\ I_{h,2} \\ \vdots \\ I_{h,n} \end{bmatrix} \tag{2.3b}$$

where this dissertation uses the notation Dg (**A**) : An $N \times N$ diagonal matrix whose entries are the N elements in the diagonal of matrix **A**, i.e., diag($[\mathbf{A}]_{1,1}$, . . . , $[\mathbf{A}]_{N,N}$) or, equivalently, diag (diag (**A**)).

Harmonic Current Emission Limits

Even if the aim is to limit the harmonic voltages in the system, it is preferred to specify harmonic current emission limits. It will be the responsibility of the system operator or owner to provide the impedance data. The individual harmonic current emission limit $E_{Ih,i}$ of harmonic order h can be expressed as

$$E_{Ih,i} = \frac{E_{Vh,i}}{Z_{hi}} \tag{2.4}$$

where $E_{Vh,i}$ and $Z_{h,i}$ are the harmonic voltage emission limits and the harmonic impedance of the system at customer “i”, respectively.

Multi-Feeder Systems

For each individual customer, only a fraction of G_{hMV} will be allowed. A reasonable approach is to take the ratio between the agreed capacity 'S_i' and the total supply capability 'S_t' in the MV system. In the single feeder systems without branch, the harmonic emission limits can be obtained by allocating the global contribution level proportionally to consumer's agreed power. However, in the multi-feeder systems, this is not valid since a component because of the harmonic current in the parallel feeders flowing in the upstream impedance. To identify the influence of the harmonic voltage emissions, which are generated by the harmonic current in the parallel feeders flowing in the upstream impedance, the allocation constant C_{hMV} and the total acceptable harmonic voltage emission level T_{EVh} are defined as

$$T_{EVh,i} = \left(\sum_{j \text{ at Bus } i} E^{\alpha}_{Vh(ij)} \right)^{\frac{1}{\alpha}} \tag{2.5}$$

where $E_{Vh(ij)} = \dfrac{Z_{hii}}{Z_{hjj}} \cdot E_{Vh(jj)} = C_j \cdot E_{Vhj}$ and $E_{Vh(jj)} = E_{Vhj}$.

In Figure 2.2, $T_{EVh,1}$ can be written as (2.6a) and the relation matrix between T_{EVh} and E_{Vh} can be written as (2.6b).

$$\begin{aligned} T_{EVh,1} &= \left(\sum_{j \text{ at Bus } 1} E^{\alpha}_{Vh(1j)} \right)^{\frac{1}{\alpha}} \\ &= \left(E^{\alpha}_{Vh11} + \cdots + E^{\alpha}_{Vh1(i-1)} + \cdots + E^{\alpha}_{Vh1n} \right)^{\frac{1}{\alpha}} \end{aligned} \tag{2.6a}$$

where E^{α}_{Vh11} is zero due to no load.

$$\begin{bmatrix} T_{EVh,1} \\ T_{EVh,2} \\ T_{EVh,3} \\ T_{EVh,4} \\ T_{EVh,5} \\ T_{EVh,6} \end{bmatrix} = \left[\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdot\cdot & 1 & \cdot\cdot & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & \cdot\cdot & 0 & \cdot\cdot & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & \cdot\cdot & 0 & \cdot\cdot & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & \cdot\cdot & 0 & \cdot\cdot & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & \cdot\cdot & 0 & \cdot\cdot & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & \cdot\cdot & 0 & \cdot\cdot & 0 \end{bmatrix} \begin{bmatrix} E_{Vh,22} \\ E_{Vh,33} \\ E_{Vh,47} \\ E_{Vh,48} \\ E_{Vh,49} \\ E_{Vh,55} \\ E_{Vh,66} \\ \vdots \\ E_{Vh,1(i-1)} \\ \vdots \\ E_{Vh,1n} \end{bmatrix}^{*\alpha} \right]^{*\frac{1}{\alpha}} \tag{2.6b}$$

where the notation $\left[A_{m\times n}\right]^{*\alpha} = \left[a_{ij}{}^{\alpha}\right]_{m\times n}$ is used.

Using (2.6), W_{VhMV} in the multi-feeder distribution system in Figure 2.2 can be defined as

$$\begin{aligned} W_{VhMV} &= \left[T^{\alpha}_{EVh,1} + T^{\alpha}_{EVh,2} + T^{\alpha}_{EVh,3} + T^{\alpha}_{EVh,4} + T^{\alpha}_{EVh,5} + T^{\alpha}_{EVh,6}\right]^{\frac{1}{\alpha}} \\ &= \left[(E^{\alpha}_{Vh,1} + C_{(i-1)}E^{\alpha}_{Vh,(i-1)} + \cdots + C_n E^{\alpha}_{Vh,n}) + \cdots + E^{\alpha}_{Vh,5} + E^{\alpha}_{Vh,6}\right]^{\frac{1}{\alpha}} \end{aligned} \tag{2.7}$$

With (2.7), since the acceptable individual harmonic voltage emission limit is proportional to the agreed power S_i of the consumer, (2.8) is fulfilled

$$G_{hMV} = C_{hMV} \cdot \left[(G^{\alpha}_{hMV} \cdot \frac{S_1}{S_t} + \cdot\cdot + C_n G^{\alpha}_{hMV} \cdot \frac{S_n}{S_t}) + \cdot\cdot + (G^{\alpha}_{hMV} \cdot \frac{S_6}{S_t}) \right]^{\frac{1}{\alpha}} \tag{2.8}$$

where $S_t = S_1 + S_2 + \cdots + S_n$.

The bus with no load is called as a pseudo-bus (only carrying the branch point designation and zero load injection.). Through (2.7) and (2.8), the acceptable harmonic voltage emission limit E_{Vh} can be easily calculated as

$$\left[\mathbf{E_{Vh}}\right] = C_{hMV} \cdot G_{hMV} \cdot \begin{bmatrix} \frac{S_1}{S_t} \\ \frac{S_2}{S_t} \\ \vdots \\ \frac{S_n}{S_t} \end{bmatrix}^{*\frac{1}{\alpha}} \tag{2.9a}$$

or, as a final result

$$E_{Vh,i} = C_{hMV} \cdot G_{hMV} \cdot \left(\frac{S_i}{S_t}\right)^{*\frac{1}{\alpha}} \tag{2.9b}$$

Through (2.5-2.8), (2.9) can be fully guaranteed to be applied to the multi-feeder distribution systems as well as single feeder systems. Regarding the agreed power S_i, Equation(2.9) clearly shows that each customer should receive the acceptable harmonic voltage emission limits proportionally to the agreed power S_i. The short-circuit power, which is the other influential factor applied as a constant power injection, is introduced in Table 2.1.

2.2.2 Set of Reference Harmonic Voltage Responses

To obtain the individual harmonic current emission limits with application of the summation exponents introduced in Chapter 2, a reference harmonic voltage response set (referred to as '$\mathbf{R_{Vh}}$' here), is defined herewith. $\mathbf{R_{Vh}}$ is used to find the weakest node in a given system, and to evaluate the allocation constant in (2.8). The influence coefficients $K_{hj\text{-}m}$ in [1] is applied to obtain the $\mathbf{R_{Vh}}$. The influence coefficient $K_{hj\text{-}m}$ is the harmonic voltage of order h, which is caused at node m when a 1p.u. harmonic voltage of order h is applied at node j. In other word, the $K_{hj\text{-}m}$ is the ratio of the impedances between the driving point impedance Z_{jj} at node j and Z_{mj}. The influence coefficients are related to the elements of the node impedance matrix of the system for the harmonic order of interest.

$$R_{Vh,m} = \left((K^{\alpha}_{h1-m} \cdot S_1) + (K^{\alpha}_{h2-m} \cdot S_2) + \cdots + (K^{\alpha}_{hn-m} \cdot S_n)\right)^{*\frac{1}{\alpha}} \tag{2.10a}$$

$$\begin{bmatrix} R_{Vh,1} \\ R_{Vh,2} \\ \vdots \\ R_{Vh,n} \end{bmatrix} = \begin{bmatrix} \left(S_1 + (K^{\alpha}_{h2-1} \cdot S_2) + \cdots + (K^{\alpha}_{hn-1} \cdot S_n)\right) \\ \left((K^{\alpha}_{h1-2} \cdot S_1) + S_2 + \cdots + (K^{\alpha}_{hn-2} \cdot S_n)\right) \\ \vdots \\ \left((K^{\alpha}_{h1-n} \cdot S_1) + (K^{\alpha}_{h2-n} \cdot S_2) + \cdots + S_n\right) \end{bmatrix}^{*\frac{1}{\alpha}} \tag{2.10b}$$

where $K_{hi-i} = \dfrac{Z_{hii}}{Z_{hii}}$.

2.2.3 Reference Harmonic Current Injection Set

With (2.10), this dissertation defines the concept of a reference harmonic current injection set (referred to as '$\mathbf{R_{Ih}}$' here). The solution set of current emission limits harmonic order h (referred to as '$\mathbf{E_{Ih}}$' here) exists on the span of the $\mathbf{R_{Ih}}$. The building method of the reference harmonic current injection set $\mathbf{R_{Ih}}$ is shown as

$$[\mathbf{R_{Ih}}] = \left[\left[[\mathbf{Z_h}]^{*\alpha}\right]^{-1} \cdot [\mathbf{R_{Vh}}]^{*\alpha}\right]^{*\frac{1}{\alpha}} \tag{2.11a}$$

$$
\begin{bmatrix} R_{Ih,1} \\ R_{Ih,2} \\ \vdots \\ R_{Ih,n} \end{bmatrix} = \left[\left[\begin{bmatrix} Z_{h,11} & Z_{h,12} & \cdots & Z_{h,1n} \\ Z_{h,21} & Z_{h,22} & \cdots & Z_{h,2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{h,n1} & Z_{h,n2} & \cdots & Z_{h,nn} \end{bmatrix}^{*\alpha} \right]^{-1} \begin{bmatrix} R_{Vh,1} \\ R_{Vh,2} \\ \vdots \\ R_{Vh,n} \end{bmatrix}^{*\alpha} \right]^{*\frac{1}{\alpha}} \tag{2.11b}
$$

Equation (2.11) can be rewritten as (2.12) without the inversion of the system impedance matrix Z_h.

$$
[\mathbf{R_{Ih}}] = \mathbf{Dg}([\mathbf{Z_h}])^{-1}[\mathbf{S}]^{*\frac{1}{\alpha}} \tag{2.12a}
$$

$$
\begin{bmatrix} R_{Ih,1} \\ R_{Ih,2} \\ \vdots \\ R_{Ih,n} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{Z_{h,11}} & 0 & \cdots & 0 \\ 0 & \dfrac{1}{Z_{h,22}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \dfrac{1}{Z_{h,nn}} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_n \end{bmatrix}^{*\frac{1}{\alpha}} \tag{2.12b}
$$

Equation (2.12) clearly shows that the reference harmonic current injection set $\mathbf{R_{Ih}}$ is the result of substituting (2.9) into (2.4) with the application of (c) in Table 2.1.

2.2.4 Short-Circuit Power

Some long MV feeders can have short-circuit powers that vary by a factor 10:1 or more from the supply side to the far end. An assessment method governing current injection along short-circuit powers is shown in the Table 2.1. For MV distribution networks with feeders of long length, changing the assessment method from (a) to (b) to (c) progressively increases the capacity of the system to tolerate disturbances but decreases the permitted harmonic emission at the far end of the feeder. If consumers having the same agreed power are allocated equal harmonic voltages according to (c), consumers at the far end of the feeder will receive much lower allocation of harmonic current then those near the substation busbar. Alternatively, if they are allocated equal harmonic current according to (a), consumers connected to the strong points (small short-circuit capacity) will be given allocations no greater than the one allocated to weak connection points and thus power system's harmonic absorption capacity would remain underutilized.

Table 2.1 : Harmonic current injection set designation

Constant Injection			
Injection Method	Current	Power	Voltage
Injection Set designation	a	b	c
I_h	K (constant)	$\frac{1}{\sqrt{Z_h}}$	$\frac{1}{Z_h}$

The approach (b) is adopted here as it gives a good tradeoff between the emission allocation to each consumer and the absorption capacity of the distribution. Adopting the (b) criterion of constant harmonic power in Table 2.1, some modifications of (2.10) should be necessary since (2.10) has been developed under the condition of the (c) harmonic current injection inversely proportional to the POE impedance in Table 2.1.

2.2.5 Harmonic Current Emission Limit Set

$\mathbf{E_{IhMV}}$ is obtained from (2.13). The percent of the customer's agreed power can be rewritten as

$$\left[\mathbf{E_{IhMV}}\right] = C_{hMV} \cdot \left[\mathbf{R_{Ih}}\right] \tag{2.13a}$$

$$[\mathbf{E_{IhMV}}] = \frac{[\mathbf{E_{IhMV}}]}{\mathbf{S}/\sqrt{3}\cdot \mathrm{V_{LL}}}\cdot 100 \quad (\%) \tag{2.13b}$$

From (2.13), the harmonic current emission limits of customer "i" is

$$\mathrm{E_{IhMV,i}} = \mathrm{C_{hMV}} \cdot \mathrm{R_{Ih,i}} \tag{2.14a}$$

$$\mathrm{E_{IhMV,i}} = \frac{\mathrm{E_{IhMV,i}}}{\mathrm{S_i}/\sqrt{3}\cdot \mathrm{V_{LL}}}\cdot 100 \quad (\%) \tag{2.14b}$$

2.2.6 Harmonic Voltage Emission Limit Set

From (2.4), the harmonic voltage emission limit E_{Vh} can be obtained as

$$[\mathbf{E_{Vh}}] = \left[\mathbf{Dg}([\mathbf{Z_h}])^{*\alpha} \cdot [\mathbf{E_{IhMV}}]^{*\alpha}\right]^{*\frac{1}{\alpha}} \tag{2.15a}$$

$$[\mathbf{E_{Vh}}] = \frac{[\mathbf{E_{Vh}}]}{\mathrm{V_{LN}}}\cdot 100 \quad (\%) \tag{2.15b}$$

2.3 Applications

Three case-studies are presented here to implement the harmonic allocation by using the proposed method. First, a test system is selected to demonstrate the distinctive features of the proposed method for evaluation of the harmonic allocation without any simplifying assumptions about network topologies (radial, meshed, or distributed generation systems). To verify the discrepancy between the proposed method and IEC 61000-3-6, a case-study system was done using IEC61000-3-6. The results indicate that the discrepancies are not insignificant. Finally, this dissertation focuses on two problems (inconsistency, unfairness) in IEEE 519 standard by contrasting it with the proposed method. This dissertation will show that inconsistency that violates the planning voltage limits can be alleviated by applying a factor similar to summation exponents. Unfairness that cannot be ignored comes from the fixed range of limits instead of formulas.

2.3.1 Basic Network Test

Radial Network

IEEE 123 bus test system [71] was selected to demonstrate the features of the proposed method with an arbitrary network. A comparison of harmonic allocation between the proposed method and IEC61000-3-6 could not be derived since latter method could not be applied to the test system because of the large number of branches and buses. IEC61000-3-6 is not easy, or even possible to implement in a distribution system with complex topology consistent with many urban networks typically found in developed countries. Table 2.2 shows that the weakest bus number is 114, and its harmonic voltage is 4%, which is the exactly same value of the G_{hMV}.

Meshed Network

Some branches are added to the test system to modify the IEEE 123 test system to become meshed. Five loops are added to the test system shown in Figure 2.3 for test purposes. The added connections are the tie lines between buses 11 and 33, buses 39 and 66, buses 37 and 59, buses 17 and 96, and buses 107 and 114. From the results of the analysis applied to this (modified) system, I hope to find general features of the meshed systems. The total capacity of E_{IhMV} has been increased since the short-circuit power in the meshed system is larger than in the non-meshed counterpart. Consequently, a meshed system operation could be advantageous when the goal is to reduce and control harmonic distortion levels.

Meshed System with DG Network

A generator, which provides pure sinusoidal voltage, is added to the previously modified meshed system shown in Figure 2.3 since there is no current emission limit for generation installations in IEC 61000-3-6. The internal voltages of a distributed generator can be treated as constant-voltage sources. The generator is considered to be linear elements whose harmonic impedance is derived similarly to passive elements in the harmonic propagation analysis. Only the generator reactance is considered in Figure 2.3. Distributed generator is added to bus 114. Table 2.2 shows the harmonic allocation results in the meshed system with DG. The index of total capacity of E_{IhMV} in a given MV systems can be applied as one of the weighting factors for a service restoration [72] and an optimal switch reconfiguration based on DAS. In the case of an emergency situation, if distribution system violates the harmonic distortion levels, the operators can control the harmonic levels by tie-switch operations using the proposed method. DG installation is also beneficial for increase of the power systems harmonic absorption capacity since it increases the short-circuit power of a given system.

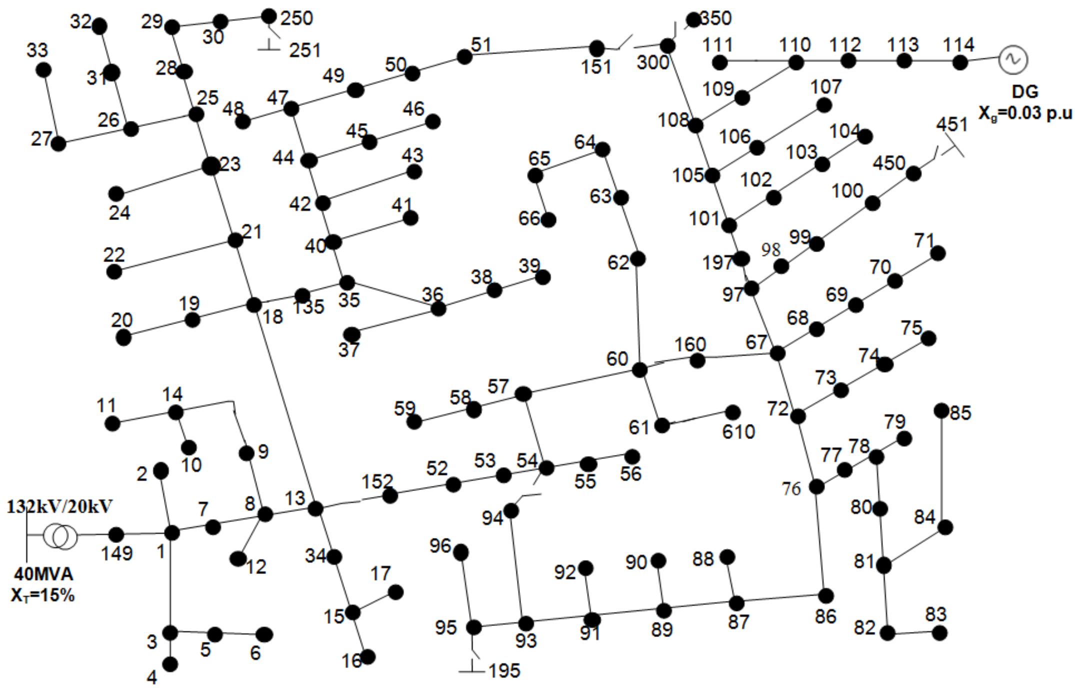


Figure 2.3 : IEEE 123-bus system with one DG

Table 2.2 : Test results of IEEE 123-bus system

Node	Load (MVA)	S_{SC} (MVA)	Harmonic Allocation							
			Radial		Meshed		DG		Meshed+DG	
			E_{IhMV}	Vh	E_{IhMV}	Vh	E_{IhMV}	Vh	E_{IhMV}	Vh
2	0.50	181	10.19	1.81	10.91	2.17	20.39	2.19	25.21	2.41
4	0.50	157	9.49	1.82	10.16	2.18	18.70	2.22	22.86	2.44
6	0.50	133	8.73	1.83	9.35	2.19	16.95	2.24	20.51	2.46
10	1.00	108	6.44	2.41	7.03	2.99	12.92	2.94	16.75	3.37
11	1.50	108	5.74	2.41	6.38	3.04	11.51	2.96	15.45	3.42
12	1.50	139	6.51	2.35	6.98	2.82	13.54	2.81	17.25	3.09
16	1.00	107	6.42	2.63	6.92	3.18	13.35	3.11	17.36	3.37
17	1.00	108	6.44	2.63	7.02	3.27	13.42	3.11	18.38	3.40
20	0.50	85	6.98	2.85	7.94	3.29	14.06	3.57	19.39	3.57
22	0.50	80	6.77	2.87	7.85	3.26	13.51	3.62	18.88	3.58
24	0.50	75	6.55	2.89	7.74	3.24	12.98	3.65	18.37	3.58
32	0.50	66	6.14	2.91	7.73	3.16	12.02	3.70	18.04	3.54
33	0.50	63	5.99	2.92	8.73	3.04	11.67	3.71	21.15	3.42
37	1.00	71	5.24	2.97	6.77	3.49	10.33	3.83	18.54	3.52
39	1.00	67	5.09	2.98	6.48	3.56	9.98	3.85	17.58	3.52
41	1.00	77	5.47	2.97	6.34	3.45	10.88	3.83	15.61	3.78
43	1.00	70	5.21	3.01	6.00	3.49	10.26	3.91	14.31	3.88
46	1.00	67	5.10	3.03	5.85	3.51	10.01	3.95	13.80	3.93
48	1.00	69	5.15	3.03	5.92	3.51	10.13	3.96	14.05	3.95
56	1.50	88	5.19	3.03	5.75	3.37	11.58	3.21	14.62	3.43
59	1.50	81	4.99	3.20	6.03	3.49	11.58	3.23	16.51	3.52
66	1.50	56	4.15	3.60	5.77	3.56	9.71	3.32	15.65	3.52
71	1.00	57	4.70	3.71	5.64	3.74	11.80	3.17	15.86	2.87
75	1.00	55	4.61	3.76	5.62	3.73	11.37	3.29	15.32	3.02
79	1.00	56	4.65	3.80	5.78	3.74	11.56	3.41	15.92	3.16
83	1.00	46	4.23	3.86	5.10	3.80	9.76	3.55	12.71	3.34
85	1.00	42	4.04	3.88	4.82	3.82	9.09	3.59	11.63	3.40
88	0.50	51	5.40	3.86	7.58	3.52	12.88	3.56	20.13	3.30
90	0.50	48	5.27	3.89	7.62	3.48	12.34	3.62	19.83	3.37
92	0.50	46	5.15	3.90	7.64	3.44	11.90	3.66	19.56	3.41
94	1.50	45	3.71	3.92	5.69	3.41	8.49	3.71	14.51	3.46
96	0.50	44	5.00	3.92	8.56	3.27	11.34	3.70	22.40	3.40
104	1.00	51	4.45	3.81	5.26	3.86	11.72	2.84	16.08	2.20
107	1.00	53	4.51	3.85	5.48	3.96	12.99	2.60	48.47	0.71
111	2.00	46	3.47	3.98	4.21	4.00	13.07	1.69	16.14	1.51
114	2.00	44	3.37	4.00	4.49	3.96	34.05	0.44	39.76	0.71
151	1.00	61	4.85	3.05	5.53	3.53	9.44	4.00	12.73	4.00
123	0.50	63	6.03	2.91	7.21	3.22	11.77	3.70	16.49	3.59
124	2.00	49	3.55	3.93	4.19	3.98	10.53	2.45	14.19	1.87
126	1.50	68	4.55	3.56	5.45	3.65	11.48	3.22	15.49	3.14
G_{hMV} : 4%, Fault level at bus 149 : 267MVA, Line : 0.6504 ohms/mile										
Linked switch sets : 11-33, 39-66, 107-114, 37-59, 17-96										
Distributed Generator (DG) : 114										

1) In this case, the given line length has been increased 10 times since some long MV feeders can have short-circuit powers that vary by 10:1 or more from the supply to the far end.

2.3.2 Investigation of IEC 61000-3-6 Limits

To compare the discrepancy between solutions, the example B.2.3 in [1] was chosen as another study. All given conditions are exactly same except the simplifying assumption of the uniformly distributed loads. The aim is to determine the 5th harmonic current allocation for a 500 kVA installation connected half-way along the feeder No. 4 where the short-circuit power is 47 MVA at POE_{13} as shown in Figure 2.4. From Table 2.3, the solution at POE_{13} solved by the proposed method is not close to the solution solved by the method in IEC61000-3-6. The result suggests that the accuracy is not sufficient to apply to the practical problems because of the simplifying assumption. The accurate solution obtained by the proposed method at POE_{13} is 6.97% and the solution calculated with the simplifying assumption is 8.63% in the study. This inaccuracy raises the harmonic voltage violation at the weakest point POE_{18} by to 23.81%.

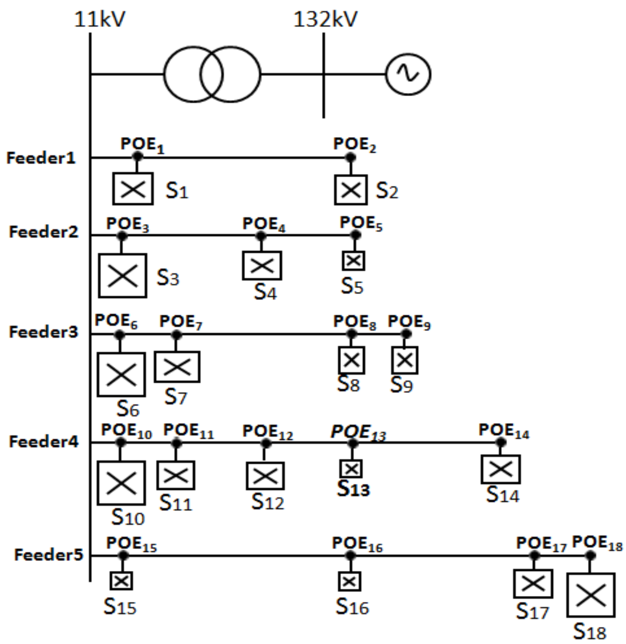


Figure 2.4 : A case-study system for investigation of IEC 61000-3-6

Table 2.3 : Test results for investigation of IEC 61000-3-6

Feeder NO.	PCC Node	Load (MVA)	S_{SC} (MVA)	Proposed Method		IEC61000-3-6 Method		Exact Solution		Error
				E_{IhMV}	V_h	E_{IhMV}	V_h	E_{IhMV}	V_h	I[1)]
1	1	2.5	120	7.03	2.56	8.70	3.17	7.03	2.56	1.67
	2	1.5	47	5.09	2.82	6.30	3.49	5.09	2.82	1.21
2	3	2.0	130	7.80	2.52	9.65	3.12	7.80	2.52	1.86
	4	1.7	70	5.99	2.72	7.42	3.37	5.99	2.72	1.43
	5	0.3	47	8.06	2.75	9.98	3.41	8.06	2.75	1.92
3	6	2.0	140	8.09	2.49	10.02	3.08	8.09	2.49	1.93
	7	1.5	130	8.46	2.52	10.48	3.11	8.46	2.52	2.02
	8	0.7	50	6.53	2.75	8.08	3.40	6.53	2.75	1.55
	9	0.8	37	5.40	2.82	6.69	3.49	5.40	2.82	1.29
4	10	2.5	140	7.59	2.50	9.40	3.09	7.59	2.50	1.81
	11	1.0	130	9.50	2.52	11.77	3.12	9.50	2.52	2.26
	12	1.0	80	7.46	2.67	9.23	3.31	7.46	2.67	1.78
	13	0.5	47	6.97	2.82	8.63	3.49	6.97	2.82	1.66
	14	1.0	28	4.41	2.99	5.46	3.71	4.41	2.99	1.05
5	15	0.5	140	12.02	2.47	14.89	3.05	12.02	2.47	2.86
	16	0.5	50	7.19	2.94	8.90	3.64	7.19	2.94	1.71
	17	1.0	25	4.17	3.70	5.16	4.58	4.17	3.70	0.99
	18	3.0	20	2.72	4.00	3.37	4.95	2.72	4.00	0.65
G_{hMV} : 4%, Fault level at the sending end: 150MVA										
Voltage Violation : 23.81%										

1) Discrepancies of EIhMV between the proposed method and the IEC61000-3-6 method.

2.3.3 Investigation of IEEE 519 Limits

In this experiment, I aim to investigate IEEE 519 limits [2]. Because of emission limits being based on different philosophies, this dissertation does not compare directly the proposed method with the method [2]. The objective of the harmonic current limits in [2] is to keep the maximum individual frequency voltage harmonic within 3% of the fundamental and the voltage THD less than 5%.

Inconsistency

From the results in Table 2.4, voltage violations might happen in the case of injecting full harmonic currents in accordance with current emission limits of IEEE 519. Table 2.4 shows that the injected current has caused the violation of the individual harmonic voltage distortion level at POE_{13} to about twice of the maximum individual voltage distortion. This example indicates that the standard may in some cases have an inconsistency problem. The same inconsistency problem is also found in the example of Sec 13.2 in [2]. If all users are injecting their full harmonic current disturbances according to the standard limits, the 5^{th} harmonic voltage distortion of user #4 in the Case A is up to 3.98% which violates the maximum voltage distortion limit. If the summation factor α=1.4 was applied, the level of the maximum voltage distortion is closer to the planning level 3%.

Unfairness

Although the short-circuit ratios (SCR) of all six customers (S_6~S_{11}) on feeder #2 are different, the harmonic current limits are all identical. In this case, large customers should be held to more stringent limits as they represent a larger portion of the total system load. Although the limits are given as a percentage of the maximum demand load current (I_L) so that large and small consumers are treated equally, the percent emission limits for large load should be less than for small load since the influence of summation factor should be considered. Loads (S_1~S_5) on feeder #1 are all different (from 0.5 to 7.0 MVA), but every current limit is identically set to 12%. All customers regardless of their short-circuit powers were allocated the same harmonic allocation limits. This indicates some unfairness in allocation of the limits under the pretext of evenhandedness.

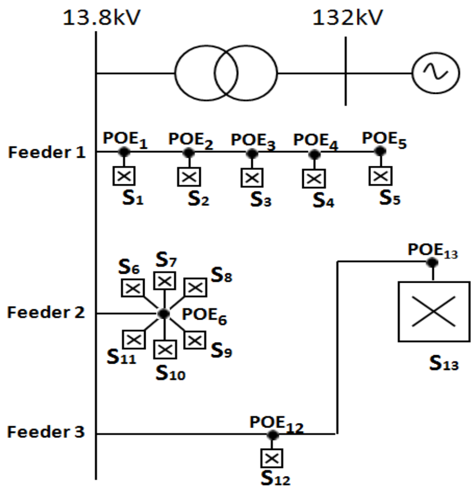


Figure 2.5 : A case-study system for investigation of IEEE Std. 519

Table 2.4 : Test results for investigation of IEEE 519

Feeder NO.	POE NO.	Load (MVA)	MVA_{SC}	I_{SC} (kA)	Isc/I_L (SCR)	IEEE 519		
						E_{IhMV}	V_h	
							$\alpha^{1)}=1$	$\alpha^{2)}=1.4$
1	1	1.5	280	12	187	12	4.15	2.06
	2	1.5	230	10	153	12	4.43	2.20
	3	1.5	200	8	133	12	4.61	2.29
	4	1.5	180	8	120	12	4.71	2.34
	5	1.5	150	6	100	12	4.81	2.40
2	6	0.5	350	15	700	12	3.83	1.91
	7	1.0	350	15	350	12	3.83	1.91
	8	1.5	350	15	233	12	3.83	1.91
	9	2.0	350	15	175	12	3.83	1.91
	10	3.0	350	15	117	12	3.83	1.91
	11	3.5	350	15	100	12	3.83	1.91
3	12	1.0	150	6	150	12	4.59	2.35
	13	7.0	50	2	7	4	6.46	3.86
5th : 3% VTHD, Fault level at the sending end: 350MVA								

1) Resulting voltage solution set evaluated by the arithmetic harmonic power flow analysis applied in IEEE Std. 519.
2) Resulting voltage solution set evaluated by the stochastic harmonic power flow analysis applied in IEC 61000-3-6.

2.4 Conclusions

The objective of the harmonic standards is to allocate the harmonic current emission limits to every customer connected to a given system so that the harmonic emissions from all distorting installations do not cause the overall system harmonic voltage levels to exceed the voltage planning levels. The harmonic emission limits for MV customers allocated in accordance with the principles of IEC 61000-3-6 remain highly suspicious as to whether the limits are accurate and general enough for all situations because of the simplifying assumption of uniformly distributed loads for MV systems.

To demonstrate the vulnerabilities and inaccuracies of the existing method of allocating the current emission limits to the MV customers in IEC 61000-3-6 and to obtain the exact harmonic emission limits, two methodologies of the reference harmonic voltage and current set have been developed based on the influence coefficient in IEC 61000-3-6. One more concept of the total individual acceptable harmonic voltage emission level has been developed to evaluate the worst voltage generated by the injection of the harmonic current emission limits under the consideration of the multi-feeder distribution systems.

This dissertation has developed the building method of the direct system impedance matrix via providing a novel mathematical model for the determination of relations between bus voltages, branch currents and bus current injections. Based on the direct system impedance matrix with the stochastic method, a number of simulations have been carried out on the IEEE 123 bus model, and an example model in IEC 61000-3-6 and IEEE Std. 519 in order to demonstrate the inaccuracies of the existing method applied with the simplifying assumption in IEC 61000-3-6.

From the evaluation results of the example model in IEC 61000-3-6, it has been demonstrated that the simplifying assumption in IEC 61000-3-6 leads the solutions to inaccuracy up to 1.66%. This inaccuracy raises the harmonic voltage violation at the weakest point by up to 23.81%. Moreover, an additional problem of the difficulty has been shown in implementing the allocation method of IEC 61000-3-6 to a large number of branches.

The results of the IEEE 123 model have verified the accuracy of the proposed method by showing that the solutions derived by the proposed method are equal to the very accurate solutions, and the value of the worst voltage distortion in the system is the same as the planning voltage level. Moreover, the simulations of various network topologies (radial, meshed, or distributed generation systems) have shown that the proposed methodologies can handle well these complex network topologies.

This dissertation has demonstrated that the voltage violation in IEEE Std. 519 can be alleviated from 6.46% to 3.86% (voltage planning level : 3%.) by applying the stochastic technique used in IEC 61000-3-6.

With an emphasis on smart grid (SM) technology, the distribution automation systems (DAS) have been increasingly used by many utilities to improve reliability and efficiency in the operation of distribution systems. The proposed method can be applied to a robust and efficient harmonic analysis program, which is very important for higher power quality (PQ). Moreover, the proposed methodologies strongly support IEC 61000-3-6 and add to its value, and could help the utilities allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently with the application of DAS.

CHAPTER 3

Comparative Analysis of Current Harmonic Emission Standards in Medium Voltage (MV) Systems

The objective of this chapter is to compare the harmonic allocation methodologies of both IEC 61000-3-6[1] and IEEE Std. 519[2]. Comparisons are carried out with analytical proofs to analyze the validity of the principles applied to both standards. The ultimate goal of harmonic standards is to fairly allocate harmonic emission limits to each customer to keep a specific voltage level in a given system. However, both standards differently approach the issue of allocating emission limits. Therefore, the solution sets derived from each of these different approaches are not identical. On the surface, it looks as though they complement each other. However, an in-depth analysis shows some significant differences.

It is impossible to directly compare both standards, since they are developed based on different methodologies. Therefore, the comparison is carried out with the key question of whether or not both solution sets ultimately arrive at the same conclusion. From the comparisons, this dissertation clearly shows the significant differences, inaccuracies and violation problems between both standards.

3.1 Introduction

All existing harmonic standards can be broadly classified into two types: standards for system levels (MV, HV-EHV systems) [1, 74] and the standard for equipment levels (LV systems) [28], which is developed in the recommended reference impedance (Z_{ref}) introduced by IEC 60725[31]. The system standards deal with the connection of customers having large harmonic-producing loads to supply systems, while the equipment standard defines the limits for the harmonic current emissions of a piece of equipment. Since all equipment, whose input current is less than 16A per phase, should be in compliance with the international equipment standard[28], the system standards[1, 74] are of more concern to power utilities at present.

In this chapter, this dissertation focuses on the two system standards (IEC 61000-3-6 and IEEE Std. 519) only for the MV allocation process. For convenience, the system harmonic standards for MV systems will be called "the standards" throughout this chapter.

Both standards should complement each other, since the only ultimate goal of both standards is to limit the actual harmonic voltage on a supply system to a specific level, which will not result in adverse effects on equipment.

Even though the goal of both standards is exactly identical, three major limits, such as the planning levels, the harmonic voltage and current emission limits differ significantly. These different approaches cause different solutions, which creates confusion in understanding to power utilities whenever their customers question the reason for these differences, since customers desperately want permission to receive much higher emission limits from their utilities. It will be necessary to re-examine the differences, accuracy and validity of both standards.

Until now, the harmonic emission limits of both standards have not been fully analyzed with analytical methods because there is still no explanation that discusses the origin of the emission limits in IEEE Std. 519, and the complex features of IEC 61000-3-6. IEEE Std. 519 can be considered as the simplest standard because the allowable emission limits are pre-calculated, but there is no rationale regarding its own emission limits [26]. IEC 61000-3-6 has detailed background information, but relies on an assumption for simplification; this assumption has defeated the excellent features of IEC 61000-3-6, since it leads the solution set to be inaccurate [75].

Note that no research can be found on a comparison of both standards with analytical proofs. Only limited studies have summarized both standards [24, 25, 33, 74]. Deterministic and stochastic harmonic flow techniques [34] are applied to analyze the resulting harmonic voltages in accordance with IEC 61000-3-6 and IEEE Std. 519, respectively. The difference of both standards, and the inconsistency and inaccuracy problems are shown, based on their own principles.

This chapter is organized into four sections. Sections 3.1 and 3.2 provide the introduction and overview, respectively. Section 3.3 carries out a comparative analysis. Conclusions are drawn in Section 3.4.

3.2 Overview

The customer is responsible for maintaining his emissions at a specified point of evaluation (POE) below the limits specified by the system operator or owner. The system operator or owner is responsible for the overall control of disturbance levels under normal operating conditions in accordance with national requirements.

The standards should be developed based on the two ultimate requirements, such as fairness (referred to as the first requirement here) and consistency (referred to as the second requirement)[1, 74]. The first requirement means that the planning levels in a given system should be fairly apportioned to each customer, proportional to his or her size of contraction. Such a criterion is related to the fact that the agreed power of a customer is often linked with his share in the investment costs of the power system. The second requirement is that the standards should insure the planning levels if all customers are in compliance with the standards. Therefore, when the system is fully loaded and all consumers are injecting up to their emission limits, the worst voltage distortion should be equal to the planning level in accordance with its own methodology.

It is impossible to directly compare both standards, since they are developed, based on different methodologies. Therefore, the comparisons are performed with the key question of whether or not both solution sets ultimately arrive at the same conclusion.

3.2.1 IEC 61000-3-6 [1]

As a technical report (TR), a large amount of space is dedicated to a description of the general principles of how to allocate the emission limits to customers connected to a supply system under consideration of the stochastic nature of harmonics.

IEC 61000-3-6 makes the emission limits more system dependant with detailed rationales, and the principles related to harmonic allocation are established (basic EMC concepts, emission limits, the summation law and global harmonic voltage contribution.) However, IEC 61000-3-6 has not been effectively applied, since it is more a set of principles than a procedure for determining harmonic allocation [76].

Moreover, the harmonic current emission limits of IEC 61000-3-6 are developed based on simplifying assumptions so that they cannot provide the exact solutions to ensure the given planning levels for all harmonic situations. In addition, the allocation presented in IEC 61000-3-6 is not developed with full consideration of the network topology so that it is impossible to apply the method to the complex network, such as the meshed and DG systems [77].

3.2.2 IEEE Std. 519[2]

Although a group leader of IEEE Std. 519 said, "The standard should stand by itself, on its own merits, with engineering proof within its pages to show it has been properly thought out with measurable benefits to those who use its guidance" [26], there is still no explanation discussing the origin of the emission limits in its own pages.

IEEE Std. 519 provides harmonic voltage and current emission limits. In the same way as IEC 61000-3-6, the IEEE Std. 519 harmonic current emission limits are related to the harmonic voltage emission limits with system impedance and customer size. Compared to IEC 61000-3-6, the emission limits of IEEE Std. 519 are simple and easy for users to use, due to the five pre-calculated harmonic voltage and current limits instead of specific formulas. With the expenses of simplicity, it is difficult to insure the two requirements.

Moreover, the emission limits are designed without full consideration of the system uncertainties, such as the size of the main transformers, the number of feeders, and the voltage level of MV systems. This is one reason why IEEE Std. 519 should use the unfair rule of, "First come, first served." To overcome this hurdle, IEEE Std. 519 should take into consideration the various system uncertainties.

Additionally, it is notable that the harmonic current emission limits are developed, assuming that there will be diversity between the harmonic currents injected by different customers. This diversity can be in the form of different harmonic components being injected, differences in the phase angles of the individual harmonic currents, or differences in the harmonic injection vs. time profiles. In recognition of this diversity, the current limits are developed so that the maximum individual frequency harmonic voltage caused by a single customer will not exceed the voltage limits for systems that can be characterized by short-circuit impedance. However, the resulting harmonic voltages are calculated, based on the deterministic method. This often leads IEEE Std. 519 to violate the second requirement.

3.3 Comparison of IEC and IEEE Limits

Comparisons are carried out based on three major procedures of both standards, as shown in Table 3.1. It is impossible to directly compare each procedure, since they are developed, based on different methodologies. Therefore, the comparisons are performed with the key question of whether or not both solution sets calculated by each standard ultimately arrive at the same conclusion.

Table 3.1 : Three procedures of both standards for the comparison

Category		IEC 61000-3-6		IEEE Std. 519
Procedure	I	Compatibility Levels Planning Levels Global Harmonic Voltage Limits	↔	Voltage Distortion Limits
	II	Harmonic Voltage Emission Limits	↔	Voltage Emission Limits
	III	Harmonic Current Emission Limits	↔	Current Emission Limits

3.3.1 Planning Levels

Planning levels are used for planning purposes in evaluating the impact on the supply system of all distorting installations. Planning levels are specified by the system operator for all system voltage levels and can be considered as internal quality objectives of the system operator. From the viewpoint of harmonic standards, determining planning levels is the most important procedure among three procedures, since the emission limits (voltage or current) for individual customers are developed on the basis of planning levels. Therefore, the planning level should be developed with good methodologies, and it should have reasonable explanations regarding the origin of the limits.

IEC 61000-3-6

The planning level is established, based on electromagnetic compatibility requirements for end-use equipment[78]. With the planning level, individual customer contribution to the overall permissible voltage distortion is allocated, based on the size of the customer relative to the capacity of the system.

Compatibility Level

The compatibility level is the specified harmonic level used as a reference level in a specified environment for coordination in the setting of emission and immunity levels. Compatibility levels are generally based on the 95 % probability levels of entire systems using distributions, which represent both time and space variations of disturbances. More detailed explanations of this essential concept can be found in [78].

Planning Level

The planning level is set to be equal to or lower than the compatibility level to give a safety margin to allow for data uncertainties and approximations used in harmonic allocation procedures. The illustration between the compatibility level and planning level is shown in Figure 3.1.

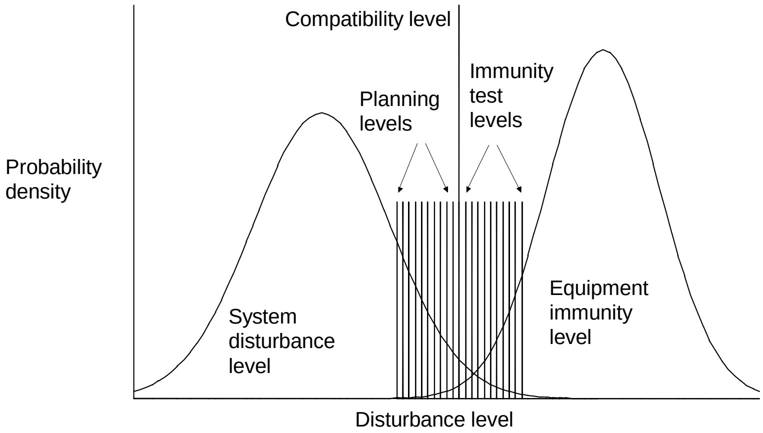


Figure 3.1 : Illustration of basic voltage quality concepts with time/location statistics covering the whole system

Only indicative values of the planning levels for MV, HV-EHV systems are given in Table 3.2 because the planning levels can be modified from case to case, depending on the system structures and circumstances.

Table 3.2 : Indicative values of planning levels for harmonic voltages in MV, HV-EHV systems

Odd harmonics non-multiples of 3			Odd harmonics multiples of 3		
Harmonic Order h	Harmonic Voltage %		Harmonic Order h	Harmonic Voltage %	
	MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2
7	4	2	9	1.2	1
11	3	1.5	15	0.3	0.3
13	2.5	1.5	21	0.2	0.2
Note : Total harmonic distortion (THD): 6.5%					

Global Harmonic Voltage Limit

Based on the planning level, it is necessary to determine the global contribution to the voltage distortion caused by the system under consideration. IEC 61000-3-6 presents the concept of the global harmonic voltage limit. Consider a typical MV system, as illustrated in Figure 3.2. The aim is to set the emission limits at the MV system.

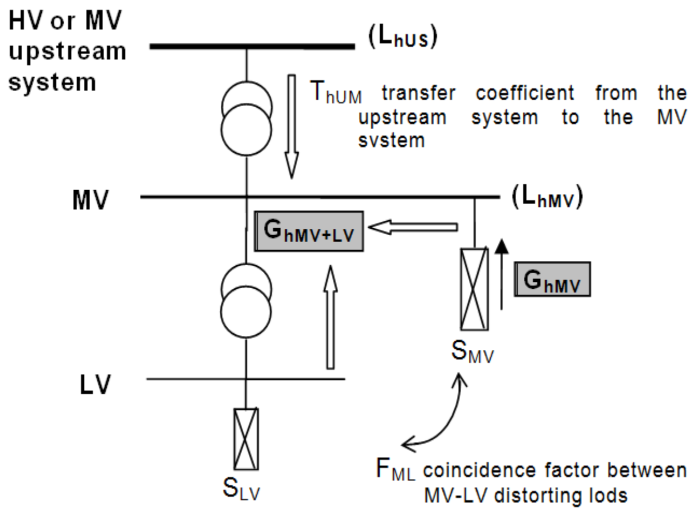


Figure 3.2 : Example for sharing global contributions

The acceptable global contribution of the local MV and LV loads in the MV system expressed in the percentage of the fundamental voltage is written as

$$G_{hMV+LV} = \sqrt[\alpha]{L_{hMV}^{\alpha} - \left(T_{hUM} \cdot L_{hUS}\right)^{\alpha}} \tag{3.1}$$

where

L_{hMV} is the planning level of the h^{th} harmonic in the MV system;

T_{hUM} is the transfer coefficient of the harmonic voltage distortion from the upstream system to the MV system;

L_{hUS} is the planning level in the upstream system; and

α is the exponent of the general summation law in [1].

The acceptable global contribution of the local loads directly supplied at MV, which is the fraction of the above global contribution, considering the possible non-simultaneity between MV and LV loads, is given by

$$G_{hMV} = \sqrt[\alpha]{\frac{S_{MV}}{S_{MV} + S_{LV} \cdot F_{ML}} \left[L_{hMV}^{\alpha} - \left(T_{hUM} \cdot L_{hUS} \right)^{\alpha} \right]} \tag{3.2}$$

where

S_{MV} is the total power of the loads directly supplied at MV through the HV/MV station transformer;

S_{LV} is the total power of the loads supplied directly at LV by the considered system; and

F_{ML} is the coincidence factor between the two distorting loads of the MV and LV distribution systems.

More explanations of the global harmonic voltage limit can be found in [1].

IEEE Std. 519

Instead of the global harmonic voltage limit, IEEE Std. 519 presents the term "voltage distortion limits." As system design values for the "worst case" for normal operation, the "voltage distortion limits" are simply defined to limit the total harmonic voltage (THD) to 5% and individual harmonic voltage to 3%, as shown in Table 3.3. Sometimes it is referred to as the five slant three criteria, or 5/3. No rationale about the background of the 5/3 criteria is presented in IEEE Std. 519.

Although the concept of "voltage distortion limits" in IEEE Std. 519 looks similar to the planning levels in IEC 61000-3-6, it is reasonable to compare both the acceptable global contribution and the voltage distortion limit, which is applied to IEC 61000-3-6 and IEEE Std. 519, respectively, while ignoring the influence of the LV system with the unit transfer coefficient [25]. However, to avoid misunderstanding the concepts between the planning level and the global harmonic voltage limit, the term "voltage distortion limits" in IEEE Std. 519 should be clearly defined.

Table 3.3 : Voltage distortion limits

Node Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3%	5%
69.001kV through 161kV	4%	3%
161.001 kV and above	3%	3%

Comparison

The comparison result of the harmonic voltage limits for both standards is shown in Table 3.4. From Table 3.4, the discrepancy at the 5th harmonic is up to 32.33%. Table 3.4 shows that the two standards have some non-negligible discrepancies from the very beginning of the planning levels. These discrepancies might be enough to lead to the divergence of emission limits. From the comparison results, to complement each other, the global harmonic voltage emissions limits of both standards should be harmonized in the near future.

Table 3.4 : Comparison of global harmonic voltage emissions in MV systems

Harmonic Order	IEC 61000-3-6 1)	IEEE Std. 519	Discrepancy
5	3.97 %	3.0%	32.33 %
7	2.85 %	3.0%	5.0 %
11	2.60 %	3.0%	13.40 %
13	2.00 %	3.0%	33.33 %

1) These results are calculated from Equation (3.2) based on Table 3.2.

3.3.2 Harmonic Voltage Emission Limits

Once global harmonic voltage limits are set, it will be allocated to each individual customer, according to the first requirement. The amount of the global harmonic voltage limit allocated to each customer is referred to as the harmonic voltage emission limit. In other words, the harmonic voltage emission limit is the resulting voltage at each customer, excluding the impacts of all harmonic current excitations, except its own.

$$\begin{aligned}[\mathbf{E_{Vh}}] &= [\mathbf{V_h}] - ([\mathbf{Z_h}] - \mathbf{Dg}([\mathbf{Z_h}])) \cdot [\mathbf{I_h}] \\ &= \mathbf{Dg}([\mathbf{Z_h}]) \cdot [\mathbf{I_h}]\end{aligned} \tag{3.3}$$

From the viewpoint of diversity between the harmonic currents injected by different customers, larger customers have more stringent limits. The harmonic current emission limit is evaluated so that the harmonic voltage emission limits caused by a single customer will not exceed the limits for a given system.

IEC 61000-3-6

The individual harmonic voltage emission limit, which is a fraction of the acceptable global contribution of the local MV customers to the h^{th} harmonic voltage in the MV system, is calculated by taking the ratio between the agreed power of the individual customer and the system capacity of the MV system. A simplified approach without considering the influence of the multi-feeder characteristic is defined as

$$E_{Vhi} = G_{hMV} \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \tag{3.4}$$

IEEE Std. 519

For the harmonic voltage emission limit, IEEE Std. 519 presents the five pre-calculated solutions, according to the number of customers connected to a given system, as shown in Table 3.5. Instead of the harmonic voltage emission limits, IEEE Std. 519 uses the term “maximum individual frequency voltage harmonic.” The maximum individual frequency voltage harmonic in IEEE Std. 519 is analogous to the harmonic voltage emission limits in IEC 61000-3-6.

Customers that are larger with respect to the capacity of the system are more strictly limited because of the impact of diversity between the harmonic currents injected by different customers.

Table 3.5 : Maximum individual frequency voltage harmonic

SCR at PCC	Maximum Individual Frequency Voltage Harmonic (%)	Related Assumption
10	2.5-3.0%	Dedication system
20	2.0-2.5%	1-2 large customers
50	1.0-1.5%	A few relatively large customers
100	0.5-1.0%	5-20 medium size customers
1000	0.05-0.10%	Many small customers

Comparison

To compare the voltage emission limits of both standards, this dissertation has developed a table similar to Table 3.5 in accordance with Equation (3.4). The voltage emission limits of IEC 61000-3-6 according to the number of customers can be evaluated, as shown in Table 3.6. By comparing Tables 3.5 and 3.6, this dissertation shows that the voltage emission limits of both standards also have a discrepancy that cannot be ignored.

Table 3.6 : Harmonic voltage emission limits (IEC 61000-3-6)[1)]

Related Assumption	Maximum Individual Frequency Voltage Harmonic (%)	Related Assumption	Maximum Individual Frequency Voltage Harmonic (%)
Dedication System	3.00%[2)]	10 large customers	0.58%
2 large customers	1.83%	20 large customers	0.35%
4 large customers	1.11%	100 large customers	0.11%
5 large customers	0.95%	1000 large customers	0.02%

1) These limits are evaluated without consideration of the multi-feeder impact based on the 5th harmonic.
2) For the purpose of comparison, I use the planning level 3%, which is equal to IEEE Std. 519 for the 5th harmonic.

3.3.3 Harmonic Current Emission Limits

The harmonic current emission limit is the centerpiece of the standards. To guarantee the second requirement, the allocation method for emission limits should be correlated with the harmonic voltage limit. Compared to IEEE Std. 519, IEC 61000-3-6 limits are more rigorously derived from the harmonic voltage limits and system impedance characteristics.

IEC 61000-3-6

As expected, in a single feeder system without any branches, the harmonic current emission limits can be simply written as

$$E_{Ihi} = \frac{E_{Vhi}}{Z_{hi}} \tag{3.5}$$

where Z_{hi} is the harmonic impedance of the system at the point of evaluation assessed, considering the actual purpose of converting the voltage to current emission limits.

To alleviate the impacts of harmonic impedance, three sets of treatment methods for impedance are presented in Table 3.7. IEC 61000-3-6 applies an injection set (b) to Equations (3.6) and (3.7).

Table 3.7 : Harmonic current assessment method

Injection Method	Current constant	Power constant	Voltage constant
Injection Set	a	b	c
I_h	K (constant)	$\frac{1}{\sqrt{Z_h}}$	$\frac{1}{Z_h}$

In case of multi-feeder systems with branches in the feeders, Equation (3.5) is no longer valid, due to the harmonic current in parallel feeders flowing in the upstream impedance. Therefore, IEC 61000-3-6 presents a general method for evaluating harmonic current emission limits as

$$E_{Ihi} = \frac{A_{hMV} S_i^{(1/\alpha)}}{\sqrt{Z_h}} \tag{3.6}$$

where

Z_h is the supply harmonic reactance at the POE; and

A_{hMV} is an allocation constant (defined below).

The allocation constant is developed with the key idea that the location of the weakest node, which will first reach the planning level as the system is loaded, will likely be at the far end of the longest feeder with the largest total agreed upon power. The allocation constant is taken as

$$A_{hMV} = \frac{G_{hMV}}{\sqrt{Z_h}\sqrt[\alpha]{S_{MVw}R_w^{0.33\cdot\alpha} + S_{MVn}R_a^{-0.3\cdot\alpha}}} \tag{3.7}$$

More detailed explanations of Equation (3.7) can be found in Chapter 1.

Although an excellent feature of this method is to contribute to calculating emission limits with handwritten calculations, an assumption of uniformly spatially distributed loads (useful for simplification), it often leads the solution set to inaccuracy [75]. The inaccuracy may lead to violating the planning levels. An additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to real distribution systems with a large number of branches and meshed systems [77]. Therefore, this dissertation use the method without any simplifying assumption for the harmonic current allocation method, which completely adheres to the principles of IEC 61000-3-6 for comparing the emission limits of both standards.

IEEE Std. 519

Unlike IEC 61000-3-6, IEEE Std. 519 presents the five pre-calculated harmonic current emission limits, based on the short-circuit ratios, as shown in Table 3.8. Due to these simple pre-calculated solutions, IEEE Std. 519 can be easily applied, but it often fails to fulfill the two requirements at the expense of simplicity, as it will be shown later.

Table 3.8 : Current emission limits

Maximum Harmonic Current Distortion in Percent of I_L						
	Harmonic order (odd Harmonics)					
Isc/I_L	<11	$11 \leq h \leq 17$	$11 \leq h \leq 17$	$11 \leq h \leq 17$	$11 \leq h \leq 17$	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
· I_{SC} : maximum short-circuit current at point of evaluation (POE). · I_L : maximum demand load current at POE.						

Comparison

To compare the solution sets of the harmonic current emission limit evaluated by both standards, a case study is carried out, based on the network topology of the IEEE 123 system [79], shown in Figure 3.3. Due to the realization of smart grids, the IEEE 123 model is modified to handle the various distribution network characteristics (i.e., radial, meshed, distributed generator, and meshed with distributed generator systems) here.

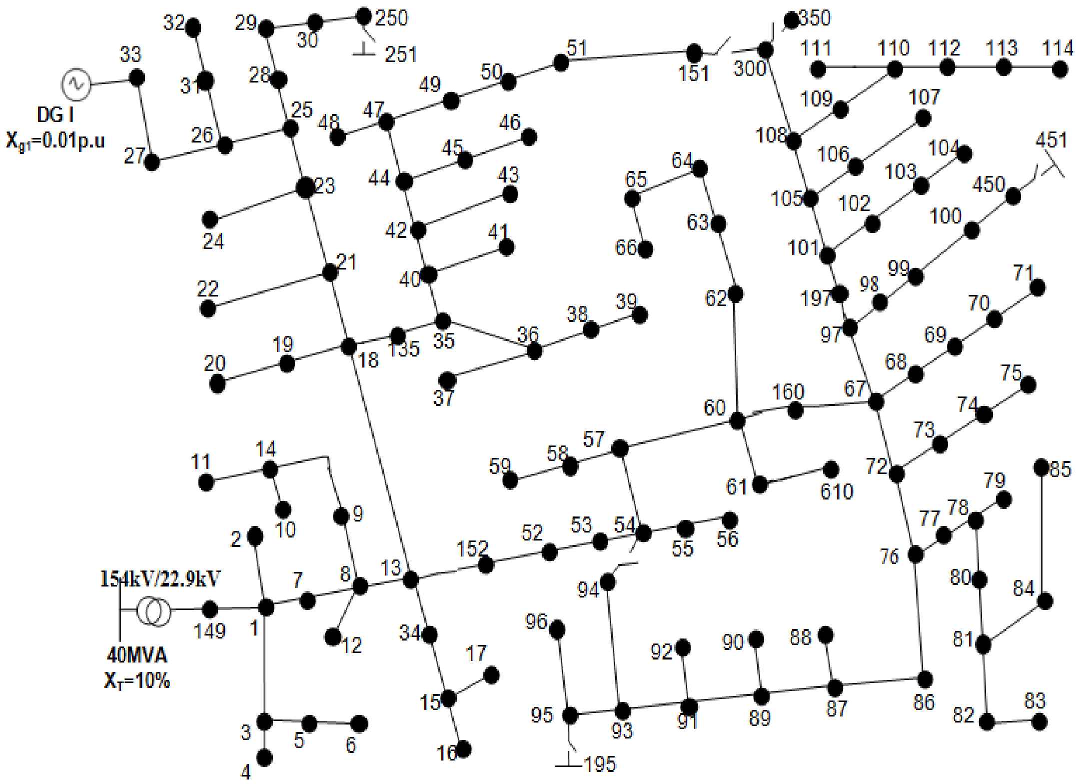


Figure 3.3 : IEEE 123 node system

For the purpose of this dissertation, this dissertation only focuses on the MV systems without the consideration of LV and HV-EHV systems. This means that the value of the global harmonic voltage level is equal to that of the planning level. To evaluate the resulting harmonic voltage at each node where a customer is connected, the current injection method with an application of the deterministic and stochastic method [78] is applied to IEEE Std. 519 and IEC 61000-3-6, respectively. For simplicity, this dissertation focuses on only 5^{th} harmonic with a planning level of 3%, as shown in Table 3.3. Based on various network topologies, such as the radial, meshed, DG and the meshed with DG system, the results of the harmonic current emission limits and the worst voltages are shown in Table 3.9.

• Radial System

From Table 3.9, the weakest node number is 114. According to IEC 61000-3-6, the worst harmonic voltage at the weakest node is 3%. However, the worst harmonic voltage according to IEEE Std. 519 is 16.2%.

• Meshed System

Three loops by linking three node sets (6-16, 17-96, 39-66) are added for implementing a meshed network. The weakest node numbers are 114 and 111. As expected, the worst harmonic voltages are 3% and 12.9% according to IEC 61000-3-6 and IEEE Std. 519, respectively.

• Distributed Generator (DG) System

A generator, which provides purely sinusoidal voltage, is added to the previously radial system, shown in Figure 3.3, since there is no current emission limit for generation installations in IEC 61000-3-6. The internal voltages of a distributed generator can be treated as constant-voltage sources. Only the generator reactance is considered, as shown in Figure 3.3. The weakest node number is 114 and 111. The worst harmonic voltage is 3% and 11.2%, according to IEC 61000-3-6 and IEEE Std. 519, respectively.

• Meshed System with the DG System

A generator is added to the previously modified meshed system. The weakest node number is 114, and the worst harmonic voltages are 3% and 8.6%.

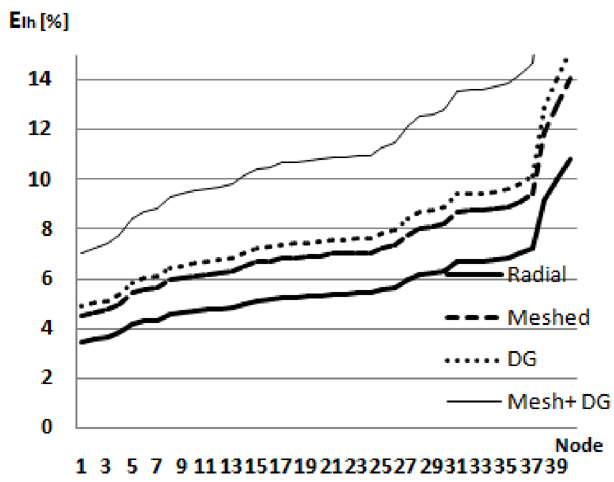
Table 3.9 clearly shows that the worst voltages in accordance with IEC 61000-3-6 are exactly equal to the planning level of 3%, regardless of the network topologies. This means that the principles of IEC 61000-3-6 can fulfill the second requirement by not violating the given planning level. However, the worst voltages evaluated by IEEE Std. 519 violate the planning level up to 3-5 times that in the case study. This result obviously shows that IEEE Std. 519 cannot guarantee the second requirement.

Table 3.9 : Harmonic current emission limits of weak nodes

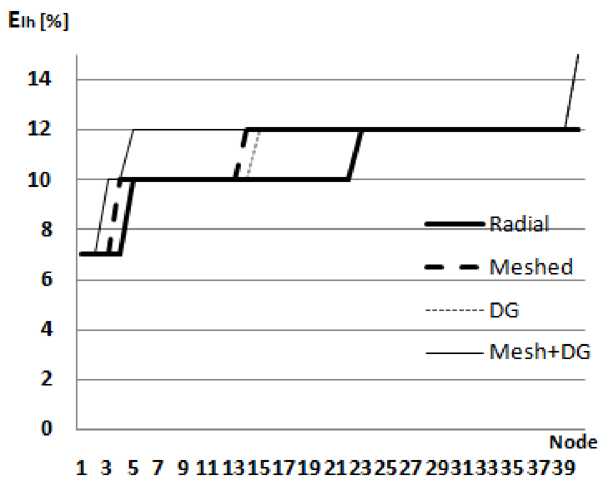
	Node	Load (MVA)	SC (MVA)	Harmonic Allocation (%)							
				Radial		Meshed		DG		Mesh+DG	
				E_{IhMV}	V_h	E_{IhMV}	V_h	E_{IhMV}	V_h	E_{IhMV}	V_h
IEC 61000-3-6	114	2.0	59.0	3.4	3.0	4.4	3.0	4.7	3.0	6.4	3.0
	111	2.0	62.0	3.5	3.0	4.6	3.0	4.8	3.0	6.7	3.0
	94	1.5	60.0	3.8	2.9	6.7	2.4	5.1	2.9	10.6	2.2
	96	0.5	58.0	5.1	2.9	10.3	2.3	6.9	2.9	17.0	2.0
	300	2.0	65.0	3.6	2.9	4.7	2.9	5.0	2.9	7.0	2.9
	92	0.5	62.0	5.3	2.9	8.9	2.4	7.2	2.9	14.0	2.2
	90	0.5	65.0	5.4	2.9	8.9	2.5	7.3	2.9	13.9	2.3
IEEE Std. 519	114	2.0	59.0	7.0	16.2	7.0	12.9	7.0	11.2	7.0	8.6
	111	2.0	62.0	7.0	16.1	7.0	12.9	7.0	11.2	7.0	8.5
	94	1.5	60.0	7.0	16.1	10.0	10.5	7.0	11.2	12.0	6.3
	96	0.5	58.0	12.0	16.1	12.0	9.9	12.0	11.2	12.0	5.8
	300	2.0	65.0	7.0	15.9	7.0	12.7	7.0	11.0	10.0	8.4
	92	0.5	62.0	12.0	16.1	12.0	10.6	12.0	11.2	12.0	6.4
	90	0.5	65.0	12.0	16.0	12.0	10.8	12.0	11.1	12.0	6.6
· GhMV : 3%, Fault level at node 149 : 291MVA, Line : 0.6504 ohms/mile · Linked switch sets : 6-16, 17-96, 39-66											

1) Detailed information regarding size of the loads of all nodes of customers is shown in Chapter 3.
2) In this case, the given line length has increased 10 times since some long MV feeders can have short-circuit power, which varies by 10:1 or more from the supply to the far end.

The entire trends of the harmonic current emission limits in Table 3.9 at all the nodes are shown in Figure 3.4. In Figure 3.4(a), the solution sets evaluated by IEC 61000-3-6 clearly demonstrate the fact of that strong systems absorb more nonlinear currents from the customers connected to the power system, as expected. A customer connected to the meshed system is allowed to emit more harmonic current than the radial system, since the meshed system is stronger than the radial system. In addition, the harmonic current emissions are well allocated, according to the size and location of each customer. Figure 3.4(a) obviously demonstrates that the harmonic current emission limits of IEC 61000-3-6 are very reasonable, according to the system strength, customer size and location. In contrast, Figure 3.4(b) shows that some customers who have different sizes and locations may receive the identical harmonic current emission limits because of the pre-calculated five solutions. In addition, the trend of the solution sets according to the system strength is not clear.



(a) IEC 61000-3-6



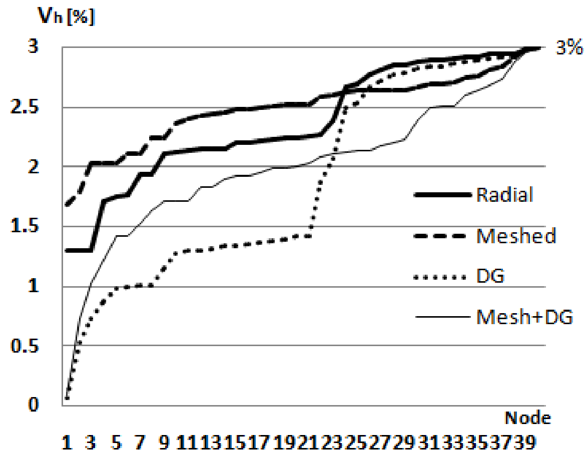
(b) IEEE Std. 519

Figure 3.4 : Harmonic current emission limits according to network topologies with respect to system strength

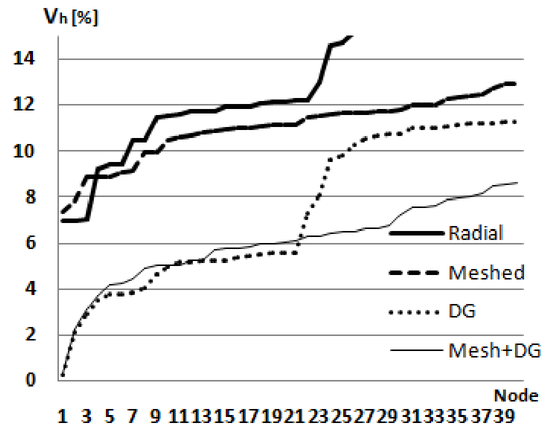
To investigate whether or not the harmonic current emission limits guarantee the second requirement, the harmonic current emission limits in Figure 3.4 are injected into the given system. To fulfill the second requirement, the resulting worst voltage distortion should be equal to the given planning level of 3%. The resulting harmonic voltages at all of the nodes where the customers are connected are shown in Figure 3.5.

Figure 3.5(a) clearly demonstrates the excellent feature of IEC 61000-3-6, since the trends of the resulting harmonic voltages are converged to the given planning level of 3%, regardless of the network topologies. This means that the principles of IEC 61000-3-6 fulfill the second requirement.

As expected, Figure 3.5(b) shows that the resulting harmonic voltages calculated by the method of IEEE Std. 519 cannot be converged to the planning levels. Moreover, the worst harmonic voltages often violate the planning levels up to 3 to 4 times. This means that all customers cannot be granted some (thought to be) reasonable share of the system's ability to absorb harmonics so that voltage distortion problems might exist with all customers within their current limits. After violation of the planning levels, it is very hard for the utilities to take an action to restore voltage quality.



(a) IEC 61000-3-6



(b) IEEE Std. 519

Figure 3.5 : Resulting harmonic voltages according to network topologies with respect to system strength

3.4 Conclusions

IEC 61000-3-6 and IEEE Std. 519 have been accepted as prevailing harmonic guidelines for interconnecting MV customers to distribution systems. However, it has been an ongoing issue for utilities as which standard they should follow, since both standards approach the same issue of allocating the harmonic emission limits differently. Moreover, the solutions derived from both are not identical. To investigate whether the solutions derived from each standard is accurate and reasonable, it is necessary to assess and compare the harmonic allocation methodologies of both IEC 61000-3-6 and IEEE Std. 519 in the MV systems.

This study has been performed to compare two standards by investigating whether they are accurate and more importantly, consistent with each other. It is impossible to directly compare both standards, since they were developed based on different methodologies. To overcome this difficulty, simulations based on the IEEE 123-bus system have been performed without any simplifying assumption, and then a comparison has been carried out to see whether the two standards result in the same outcome.

From the results of comparison, differences in the value of the planning levels, voltage emission limits, and current emission limits between both standards have been demonstrated. The planning levels of both standards have discrepancies up to 67%. Significant differences of the resulting voltages have been shown by the huge discrepancies of the voltages up to over 400%.

The resulting solutions have shown that the principles of IEC 61000-3-6 fulfill the requirement of ensuring the voltage planning level. However, IEEE Std. 519 fails to fulfill the voltage planning level.

To analyze both standards, the representative distribution model with multi-feeders has been developed under the consideration of the following uncertainties of distribution systems: a) the power supply capacity, b) feeder lengths, c) customer numbers, and d) customer sizes.

A number of simulations via Monte-Carlo technique to consider the uncertainties in distribution systems on the representative distribution model have been carried out to identify what the structural vulnerabilities are and how to improve the weaknesses of both standards so that both of them make the systems stable if all customers are in compliance with the guidelines from four different perspectives: a) system harmonic absorption capability, b) the level of the worst voltage distortion, c) inaccuracy, and d) sufficiency of the examples of the standards.

From the resulting trends of the relationship between the system harmonic absorption capability and the power supply capacity, it has been demonstrated that IEC 61000-3-6 has a function to control the system harmonic absorption capability by controlling the current emission limits. However, the resulting solutions evaluated by IEEE Std. 519 has demonstrated the inconsistency by failing to keep its own planning levels when all customers inject their own emission limits into distribution systems , since it has no function to control the current emission limits according to the power supply capacity.

CHAPTER 4

Correction Factors for Improving the Harmonic Current Emission Limits of IEEE Std. 519 in MV Systems

The objective of this chapter is to propose correction factors to improve the harmonic current emission limits of IEEE Std. 519 [2] in MV systems.

IEEE Std. 519 takes the simple deterministic method, which often leads to unrealistically high values, especially at high harmonic orders. Moreover, due to the cost of being simple and universal pre-calculated harmonic current emission limits, IEEE Std. 519 cannot fully consider the precarious nature of distribution systems in its own emission limits. Therefore, the emission limits of IEEE Std. 519 often boost voltage distortions theoretically up to twice beyond planning levels.

This dissertation proposes the necessity to apply the stochastic method in IEC 61000-3-6 [1] to IEEE Std. 519, and show the results of IEEE Std. 519 emission limits, based on the stochastic harmonic flow. In addition, three correction factors are developed to compensate for the influences of the following uncertainties of distribution systems on the harmonic current emission limits: the variation of the main transformer size (referred to as supply capacity here), the number of feeders, and system voltage levels.

The feasibility of the correction factors proposed is obviously proven, based on a multi-feeder model of distribution systems with the Monte-Carlo method. The proposed methods strongly adhere to IEEE Std. 519 and add to its value, and could help power utilities allocate harmonic current emission limits to their own customers more reasonably, accurately and efficiently.

4.1 Introduction

IEEE Std. 519[2] has been applied as a well-known harmonic standard, along with IEC 61000-3-6[1]. IEEE Std. 519 is considered as the simplest standard because the allowable emission limits are pre-calculated.

Contrary to our expectation, it is not easy for users to apply IEEE Std. 519 to practical systems because there is still no explanation that discusses the origin of the emission limits in IEEE Std. 519. Therefore, users cannot be confident of whether or not they can apply the emission limits of IEEE Std. 519 to their systems without any modification under consideration of their system structures and circumstances.

This is why power utilities tend to assess compliance with their customer's installation in case a harmonic problem happens or is expected instead of whenever a customer is connected. In addition, due to the stochastic nature of harmonics, the harmonic standards should be designed with the statistical distribution of voltages resulting from dispersed and random current sources. It is a well-known fact that the sum of a number of harmonic currents with the arithmetic sum of the maximum values generally leads to more than some statistical variations.

A simple arithmetic method is adopted to evaluate resulting voltage distortions in the application examples of Sec 13.2 in IEEE Std. 519[2]. This often leads to unrealistically high values of the resulting voltage distortions. To overcome this obstacle, This dissertation proposes a method of how to apply the stochastic method of IEC 61000-3-6 (referred to as the general summation law) to IEEE Std. 519.

Moreover, at the expense of simplicity, it is impossible for IEEE Std. 519 to fully consider the following random nature of distribution systems: a) supply capacities; b) the number of feeders; and c) system voltage levels. To include the impacts of the uncertainties on the emission limits of IEEE Std. 519, this chapter proposes three correction factors: the supply capacity, the multi-feeder and the system voltage.

Until now, the harmonic emission limits of IEEE Std. 519 have not been analyzed with analytical methods because there is no rationale regarding the origin of the emission limits in IEEE Std. 519. An essential summary of IEEE Std. 519, including the recommended limits and the procedures, was introduced in [80, 81]. The need to improve the deterministic method applied in IEEE Std. 519 was proposed in [82]. Note that no research can be found in terms of improving the emission limits of IEEE Std. 519.

This chapter consists of five sections. Sections 4.1 and 4.2 provide the introduction and basic concepts. Section 4.3 introduces the general summation law. Section 4.4 proposes three correction factors. Conclusions are drawn in Section 4.5.

4.2 Basic Concepts

For convenience, the harmonic current emission limits will be referred to as the emission limits in this chapter. The consumers are responsible for maintaining their emission limits at the point of evaluation (POE) below the voltage distortion limits specified by the utilities. The utilities are responsible for the overall control of the voltage distortion levels under normal operating conditions in accordance with national requirements. The primary objective of the harmonic standards is to limit the emission limits so as not to violate a specific voltage distortion level that would result in adverse effects on equipment.

The harmonic standards should fulfill the following two rules.

Rule I: Fairness

The voltage emission limits should be allocated to each customer to the agreed power of customers. This means that the planning levels in a given system should be fairly shared with each customer, according to his or her size of contraction.

Rule II: Consistency

The harmonic standards should insure a specific voltage distortion level (referred to as the planning level), which will not result in adverse effects on equipment, if all customers are in compliance with the standard.

It is impossible to analyze the solutions of the IEEE Std. 519 emission limits because there exists no rationale about its own limits. Therefore, analyses are carried out with the key criteria of whether or not the solution set of IEEE Std. 519 ultimately fulfills *Rule II*.

4.2.1 Emission limits of IEEE Std. 519

The emission limits of IEEE Std. 519 are designed to limit the maximum individual frequency voltage harmonics to 3% of the fundamental and THD to 5% for systems without a major parallel resonance at one of the injected harmonic frequencies. Table 4.1 shows that the emission limits can be evaluated under consideration of the short-circuit ratio (I_{SC}/I_L) without considering three uncertainties.

Table 4.1 : Current emission limits for MV systems

Maximum Harmonic Current Distortion in Percent of I_L						
	Harmonic order (odd Harmonics)					
Isc/I_L	<11	11≤h≤17	11≤h≤17	11≤h≤17	11≤h≤17	THD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
· I_{SC} : maximum short-circuit current at point of evaluation (POE). · I_L : maximum demand load current at POE.						

4.2.2 Multi-feeder Model

To investigate the influence of each uncertainty on the emission limits, simulations are carried out, based on the multi-feeder model of distribution systems. From the resulting voltage distortion at the weakest node in a given system, this dissertation can make sure as to whether or not solutions fulfill *Rule II*. Although the IEEE123 model [79] has an advantage of easily changing the network topology by connecting each node, it does not represent the practical distribution system well because it is only the single feeder system. Therefore, this dissertation developed the multi-feeder model, which can represent distribution systems , as shown in Figure 4.1. The features of the multi-feeder model are the following:

• It consists of five feeders. The number of feeders can be changed from one to five for simulation.

• Implementing load densities, such as a) urban areas (Feeder No. 3), b) suburban areas (Feeder Nos. 1, 2, and 4), and c) rural areas (Feeder No. 5).

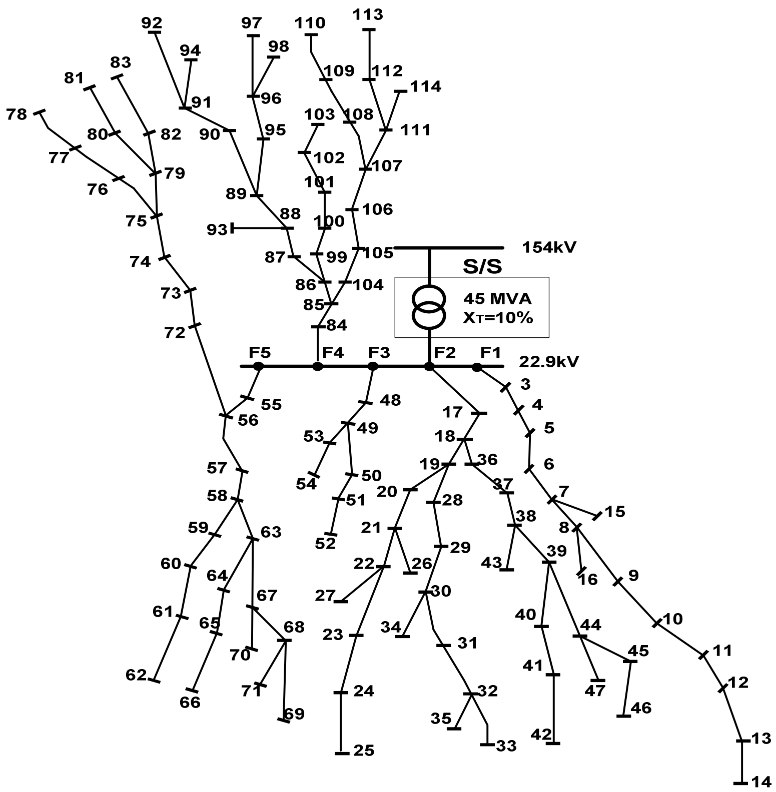


Figure 4.1 : Multi-feeder model for distribution systems

4.2.3 Monte-Carlo Technique

To obtain more representative results, the Monte-Carlo method is used on the multi-feeder model. For Monte-Carlo simulations, three variables, which IEEE Std. 519 considers, are chosen, as shown in Table 4.3.

For randomly implementing short-circuit impedances, the section lengths can be varied from 0.1 to 3.0 km. In other words, the length of Feeder No.1 in Figure 4.1 can be changed from 1.2 to 36km. The number of customers and the node where a customer will be connected are randomly chosen. The size of a customer is randomly allocated within the supply capacity.

Table 4.2 : Variables for Monte-Carlo Simulations

Variables	Min	Max	Condition
Section Length[1)] (Fault level)	0.1 km	3.0 km	Uniformly Distributed
Customer Numbers	1	Node Number[2)]	
Customer Size (Agreed Power)	0 kVA	Feeder Capacity[3)]	

1) Assume that every section length is identical. Each section length is 1 Km. This means that the length of the first feeder in Figure 4.1 is 12 Km.
2) The maximum node number is determined according to the number of nodes in each feeder.
3) For simplification, the value of the supply capacity divided by the feeder number is the feeder capacity.

4.2.4 Random Nature of Harmonics

When many customers producing harmonic currents are present in the same distribution system, the harmonic current in the lines and the harmonic voltage at the point of evaluation (POE) depends on the superposition effect caused by different amplitudes and phase angles of the currents emitted from different sources. An exact evaluation of the resulting harmonic voltages (vectorial sums) is restricted only to a few special cases. Taking the algebraic sum of the contributions by each harmonic source may lead to unrealistically high values, especially at high harmonic orders. Therefore, the summation problem should be considered when studying the connection of a new customer load producing harmonics. Consequently, statistical techniques for harmonic power flow analysis are more suitable and practical.

4.2.5 Random Nature of Distribution Systems

This dissertation presents three uncertainties that IEEE Std. 519 does not fully consider on its own emission limits. Then, this dissertation investigates the influences of the random nature of distribution systems in order to develop correction factors to compensate for the impacts of these three uncertainties on emission limits.

4.2.6 Supply Capacity

In a given system, the size of the supply capacity can be generally determined according to the size and number of customers. Therefore, increasing the supply capacity means that the size and number of customers connected to the distribution system also increase. Then, the resulting harmonic voltage levels will rise because of the increased emission limits generated by the increased customer number. To guarantee *Rule II,* regardless of the supply capacity, IEEE Std. 519 should have a function to control the emission limits according to the supply capacity.

4.2.7 Number of Feeders

Distribution systems are designed with the concept of multi-feeder systems. Under same system condition, when the number of feeders is increased, the total emission limits are increased, since the system becomes stronger. Therefore, to guarantee *Rule II,* regardless of the influence of the feeder numbers, IEEE Std. 519 should have a function to control the emission limits according to the number of feeders.

4.2.8 Voltage Levels

The range of the nominal voltage level for MV systems is between 1 kV and 35 kV according to IEC [1]. When the level of the system voltage is increased, the system will be stronger. A strong system can absorb more nonlinear current from customers connected to the power system. For example, the meshed system is stronger than the radial system. A customer connected to the meshed system will be allowed to emit more harmonic current than a customer connected to the radial system. Therefore, the emission limits should be apportioned under consideration of the system voltage levels.

4.3 Summation Law

IEEE Std. 519 is conducted with a deterministic method, based on the worst case. This might provide a safety margin in the system design and operation. However, this often leads to overdesign and excessive costs. Consequently, statistical techniques for harmonic analysis are more practical. IEC 61000-3-6 treats harmonics as randomly varying phasors that act as stochastic quantities. This contrasts with IEEE Std. 519. In this section, this dissertation briefly introduces the basic concept of the general summation law, which is applied to IEC 61000-3-6.

4.3.1 General Summation Law

Two summation laws for evaluating the summation of a number of harmonic sources are introduced in IEC 61000-3-6 [73]. The first summation law [1, 34, 83] is a simple linear law making use of diversity factors. The approach using diversity factors may be especially useful with the phase angles of the already existing (background) harmonics. The second method [1, 34, 83] is developed, based on the Monte-Carlo approach, considering that the compatibility level has to be met with a probability of 95% or better [35]. The second summation law (referred to as the general summation law) is more general and combines the harmonic contributions from non-linear loads; thus, it is considered to be more applicable in most circumstances, since it does not consider the load types. IEC 61000-3-6 recommends the general summation law for voltages and currents A:

$$A_h = \left(\sum_{i=1}^{n} (A_{h,i})^{\alpha} \right)^{\frac{1}{\alpha}} \tag{4.1}$$

where

$A_{h,i}$ is the magnitude of the various individual emission levels (order h) to be combined; and

α is the exponent of the summation law.

More detailed explanations of the general summation law can be found in [1].

4.3.2 Arithmetic and Stochastic Harmonic Flow Analysis

To analyze the resulting harmonic voltages based on arithmetic and stochastic harmonic flow analysis, a case study is carried out with the multi-feeder model shown in Figure 4.1. To avoid complexity, this dissertation focuses on the 5^{th} harmonic without consideration of the influence of the LV and HV-EHV systems. The solution set of the resulting voltage evaluated by the arithmetic and stochastic methods (the general summation law) are shown in the eighth and ninth columns in Table 4.3, respectively.

From the results, this dissertation obviously recognizes that it is very impractical to use the deterministic method in IEEE Std. 519, since the worst voltage (7.29%) violates the planning level (3.0%) by nearly twofold in the given multi-feeder model. Note that the violation level depends on the system structures and circumstances.

In contrast, an excellent feature of the stochastic method is clearly demonstrated by showing that the worst voltage (2.96%) nearly approaches the planning level (3%). The simple arithmetic approach has defeated IEEE Std. 519, since it theoretically leads the voltage distortion level to be higher than practical applications.

The trend of the resulting voltages obviously shows that the general summation law applied in IEC 61000-3-6 should be applied to IEEE Std. 519 to obtain more reasonable results. Therefore, the stochastic method is applied to develop the correction factors in this chapter.

Table 4.3 : Comparison between arithmetic and stochastic methods

Node	Load[1] (MVA)	S_{SC} (MVA)	I_L (A)	R_{SC}[2]	Harmonic Allocation			
					IEEE Std. 519 Emission Limits		Voltage Distortions (%)	
					(%)	(A)	V[3]	V[4]
4	4.00	258.59	100.85	64.65	10.00	10.08	6.20	2.44
14	2.00	82.70	50.42	41.35	7.00	3.53	7.22	2.96
15	2.00	139.73	50.42	69.86	10.00	5.04	6.85	2.76
16	1.00	125.33	25.21	125.33	12.00	3.03	6.92	2.79
18	2.50	258.59	63.03	103.44	12.00	7.56	6.38	2.42
21	0.50	157.87	12.61	315.74	12.00	1.51	6.90	2.62
25	0.50	103.91	12.61	207.81	12.00	1.51	7.04	2.68
26	1.00	139.73	25.21	139.73	12.00	3.03	6.94	2.64
27	1.00	125.33	25.21	125.33	12.00	3.03	7.02	2.67
33	0.50	103.91	12.61	207.81	12.00	1.51	6.94	2.62
34	0.50	125.33	12.61	250.65	12.00	1.51	6.85	2.58
35	0.50	103.91	12.61	207.81	12.00	1.51	6.94	2.62
42	0.50	103.91	12.61	207.81	12.00	1.51	6.82	2.57
43	0.50	139.73	12.61	279.46	12.00	1.51	6.70	2.52
46	0.50	103.91	12.61	207.81	12.00	1.51	6.85	2.58
47	0.50	113.62	12.61	227.23	12.00	1.51	6.82	2.57
49	5.00	258.59	126.06	51.72	10.00	12.61	6.23	2.50
52	2.00	157.87	50.42	78.94	10.00	5.04	6.48	2.63
54	2.00	181.43	50.42	90.71	10.00	5.04	6.39	2.59
56	3.00	258.59	75.64	86.20	10.00	7.56	6.33	2.40
62	0.50	113.62	12.61	227.23	12.00	1.51	6.77	2.56
63	1.00	157.87	25.21	157.87	12.00	3.03	6.82	2.58
66	0.50	113.62	12.61	227.23	12.00	1.51	6.90	2.61
69	0.50	113.62	12.61	227.23	12.00	1.51	6.97	2.64
70	0.50	125.33	12.61	250.65	12.00	1.51	6.92	2.62
71	0.50	113.62	12.61	227.23	12.00	1.51	6.97	2.64
75	1.00	139.73	25.21	139.73	12.00	3.03	6.82	2.59
78	0.50	103.91	12.61	207.81	12.00	1.51	6.90	2.62
81	0.50	103.91	12.61	207.81	12.00	1.51	6.92	2.63
83	0.50	103.91	12.61	207.81	12.00	1.51	6.92	2.63
85	2.00	258.59	50.42	129.30	12.00	6.05	6.38	2.40
89	1.00	139.73	25.21	139.73	12.00	3.03	7.17	2.69
92	0.50	103.91	12.61	207.81	12.00	1.51	7.29	2.74
93	1.00	139.73	25.21	139.73	12.00	3.03	7.07	2.66
94	0.50	103.91	12.61	207.81	12.00	1.51	7.29	2.74
97	0.50	103.91	12.61	207.81	12.00	1.51	7.29	2.74
98	0.50	103.91	12.61	207.81	12.00	1.51	7.29	2.74
99	0.50	181.43	12.61	362.85	12.00	1.51	6.67	2.50
103	0.50	113.62	12.61	227.23	12.00	1.51	6.77	2.54
107	0.50	139.73	12.61	279.46	12.00	1.51	6.77	2.53
110	0.50	103.91	12.61	207.81	12.00	1.51	6.85	2.56
113	0.50	103.91	12.61	207.81	12.00	1.51	6.87	2.57
114	0.50	113.62	12.61	227.23	12.00	1.51	6.85	2.56
Worst voltage distortion							7.29	2.96

1) Total loads are equal to the capacity of the main transformer in Figure 4.1.
2) Line: ACSR 165 mm2 (0.431 ohm /Km), Section length: 1Km.
3) The voltage solution set evaluated by the deterministic method of IEEE. Std. 519.
4) The voltage solution set evaluated by the general summation law (a=1.4).

4.4 Correction Factors

In practice, utilities cannot assign uncertainties of distribution systems; thus, the harmonic standards should consider the influence of these uncertainties. It is impossible to check whether or not the emission limits of IEEE Std. 519 consider the influence of these uncertainties because of the absence of a rationale of its own emission limits. The only way is to investigate whether or not the emission limits of IEEE Std. 519 fulfill *Rule II*.

To obtain representative results, the Monte-Carlo method with three variables (according to Table 4.4) is used, based on the multi-feeder model in Figure 4.1. The selected ranges in Table 4.4 are enough to represent the characteristic of practical distribution feeders.

Table 4.4 : Three uncertainties for distribution systems

NO	Uncertainty Category	Ranges		
		Min	Max	Step
1	Supply capacity	10MVA	80 MVA	10MVA
2	Number of Feeders	1	8	1
3	System Voltage Level	11kV	26kV	3kV

Figure 4.2. shows the entire process of how to evaluate the correction factors and the modified emission limits of IEEE Std. 519.

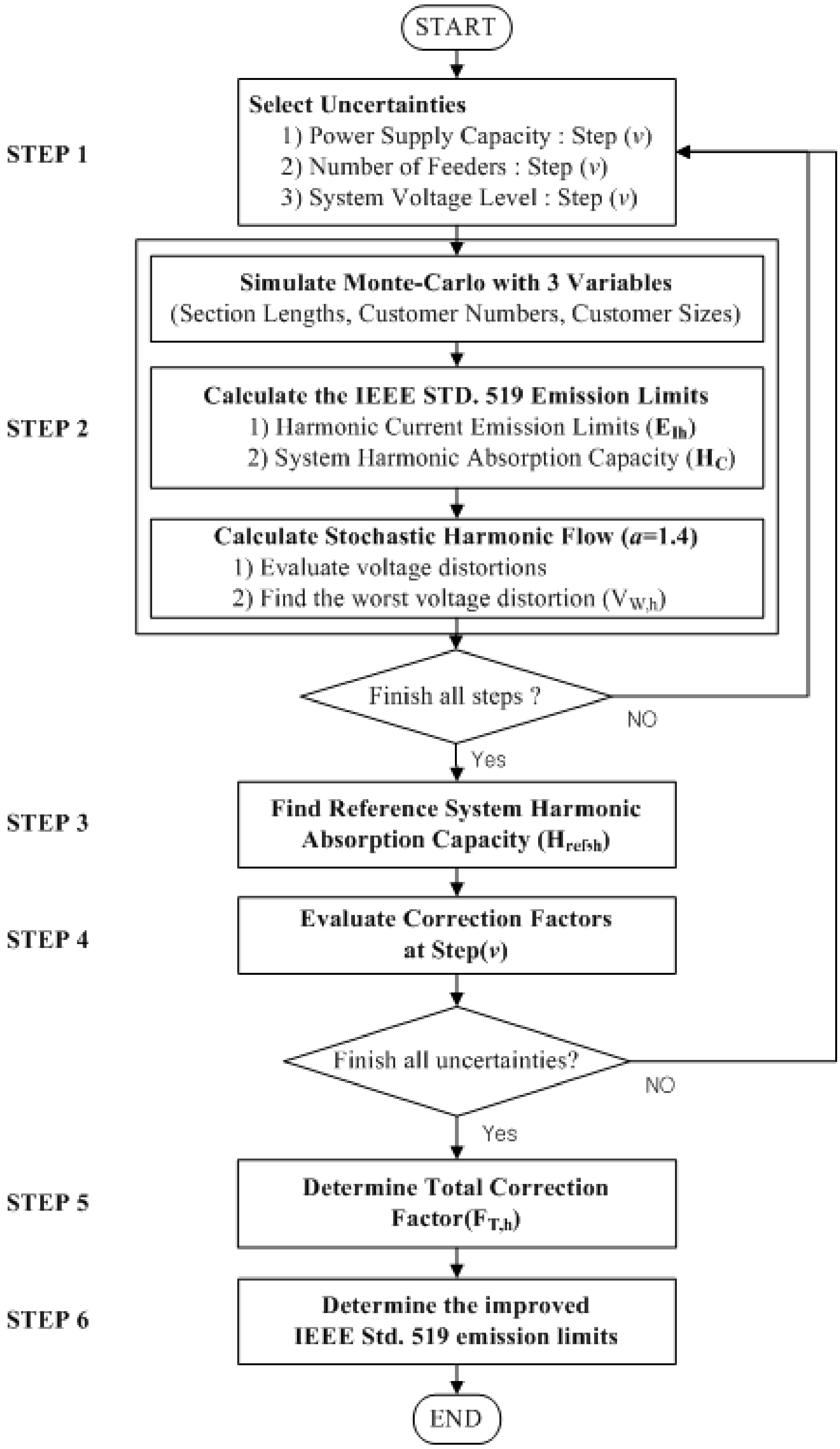


Figure 4.2 : Procedure for obtaining the correction factors

4.4.1 Supply Capacity

In this dissertation, the supply capacity can be defined as

$$P_C = \sum_{i=1}^{N} P_i \tag{4.2}$$

where P_i and N are the subscribed power of the concerned customer "i" and the number of customers on the system, respectively.

The system harmonic absorption capacity can be defined as

$$H_{C,h} = \sum_{i=1}^{N} E_{Ih,i} \tag{4.3}$$

where $E_{Ih,i}$ represents the individual emission limits of IEEE Std. 519 at customer "i."

If the emission limit is designed to be determined without consideration of the supply capacity, increasing the supply capacity leads to increasing the emission limits injected into the power system. Consequently, the increased emission limits may lead to a violation of *Rule II*. Therefore, in order to guarantee *Rule II,* regardless of the variation of the supply capacity, IEEE Std. 519 has a function to control the emission limits according to the supply capacity.

Based on IEEE Std. 519, the results of the trends of voltage distortions according to each supply capacity are shown in Figure 4.3. As expected, the simulation results clearly demonstrate that the worst resulting voltage distortion is directly proportional to the size of the power supply capacity. This causes the violation of *Rule II,* since IEEE Std.

519 has no function to control the emission limits in accordance with the size of the power supply capacity.

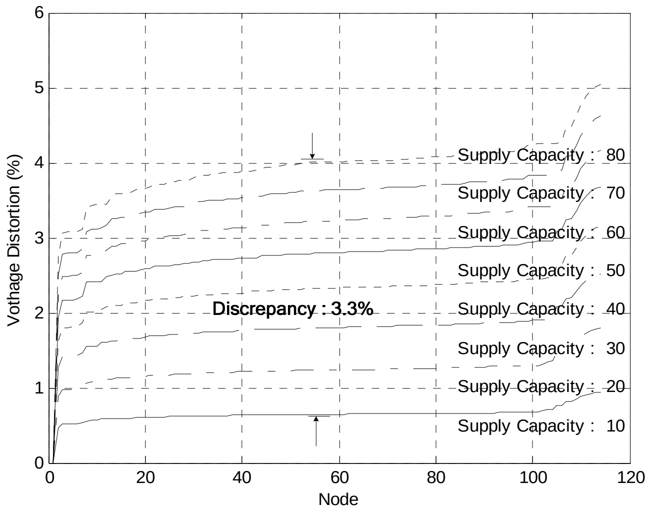


Figure 4.3 : Representative trends of voltage distortions according to the sizes of supply capacities

To compensate for the impact of the supply capacity on the emission limits, this dissertation proposes the supply capacity correction factor. The system harmonic absorption capacity ($H_{C,h}$), which makes the worst harmonic voltage ($V_{W,h}$) equal to the planning level, is defined as the reference system harmonic absorption capacity ($H_{ref,h}$) here. In Table 4.5, the reference system harmonic absorption capacity capacity in the given system is 106.24A at the supply capacity (37MVA). To compensate for the emission limits in accordance with the size of the supply capacity, the correction factor of the supply capacity at each step (v) is defined as

$$F_{P,h}^{(v)} = \frac{H_{ref,h}}{H_{C,h}^{(v)}} \tag{4.4}$$

Table 4.5 : Correction factors for power supply capacity

Step (MVA)	$H_{C,h}$ (A)	$V_{W,h}$ (%)	$F_{P,h}$	Step (MVA)	$H_{C,h}$ (A)	$V_{W,h}$ (%)	$F_{P,h}$
10	31.97	0.95	3.323	40	113.50	3.12	0.936
15	46.39	1.39	2.290	45	125.20	3.40	0.849
20	60.62	1.79	1.753	50	136.50	3.69	0.778
25	74.57	2.18	1.425	55	147.23	3.93	0.722
30	88.07	2.52	1.206	60	157.77	4.18	0.673
35	101.07	2.83	1.051	65	167.76	4.39	0.633
36	103.64	2.90	1.025	70	177.89	4.63	0.597
37	106.24	2.95	1.000	75	187.00	4.84	0.568
38	108.59	3.02	0.978	80	196.09	5.05	0.542

With the application of the correction factors, the new emission limits of IEEE Std. 519 can be evaluated as

$$E_{Ih,i}^{New} = F_{P,h} \cdot E_{Ih,i} \tag{4.5}$$

With (4.5), the new harmonic absorption capacity at each step (v) can be written as

$$H_{C,h}^{New(v)} = \sum_{i}^{N} F_{P,h}^{v} \cdot E_{Ih,i}^{New(v)} \tag{4.6}$$

The resulting voltage distortions generated by injecting the new emission limits evaluated by Equation (4.5) are shown in Figure 4.4. The trends of the resulting voltage distortions clearly demonstrate the excellent feature of the proposed correction factor by showing that the worst resulting voltage distortions at all of the steps nearly approach the planning level (3%), regardless of the size of the supply capacity.

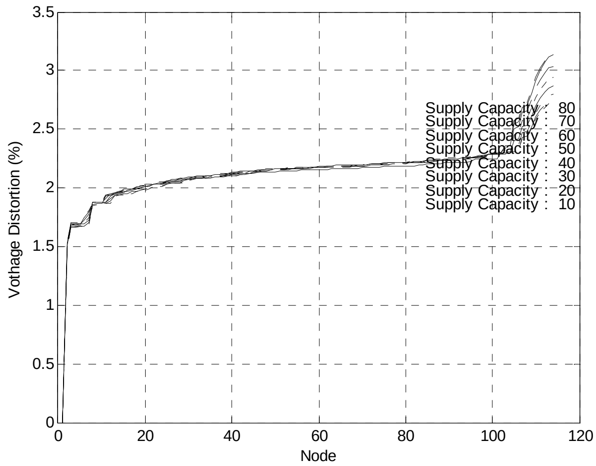
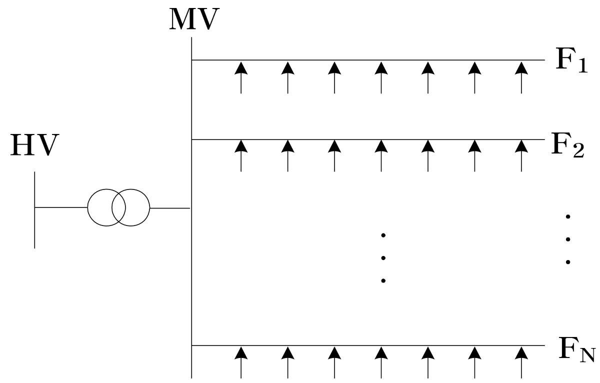


Figure 4.4 : Representative trends of voltage distortions modified by the correction factor of supply capacities

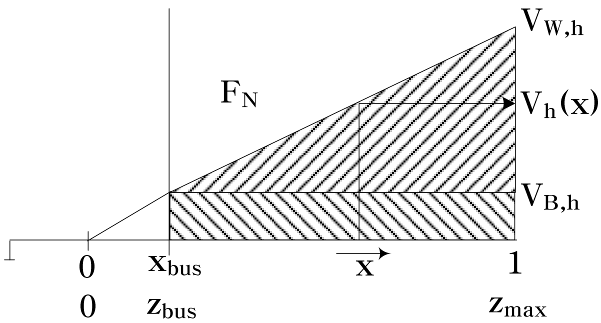
4.4.2 Multi-feeder Systems

To analyze the relationship between the system harmonic absorption capacity and the number of feeders, a formula is presented, based on a simple multi-feeder system, as shown in Figure 4.5 [84]. Although Figure 4.5(a) is far from the practical distribution system, it is enough to show the influence of multi-feeder systems on the emission limits. For simplicity, the following are assumed.

- All feeders are identical
- The load is uniformly distributed along the line section
- The impedance increases linearly from the busbar.



(a) Multi-feeder system



(b) Equivalent circuit at the h^{th} harmonic order

Figure 4.5 : Scheme of MV multi-feeder systems

The system harmonic absorption capacity is equal to the current at the busbar, since all of the emission limits according to IEEE Std. 519 are added at the busbar, where all feeders are connected to the main transformer. In Figure 4.5(b), the harmonic current $i_h(x)$ can be expressed as

$$i_h(x)=\begin{cases} H_{C,h} & : 0 \le x \le x_{bus} \\ \dfrac{H_{C,h}}{N_F}\cdot\left(\dfrac{x-1}{x_{bus}-1}\right) & : x_{bus} \le x \le 1 \end{cases} \tag{4.7}$$

where N_F is the number of feeders.

The background voltage distortion at the busbar can be obtained as

$$V_{B,h}(x_{bus}) = h \cdot H_{C,h} \cdot x_{bus} \cdot Z_{max} \tag{4.8}$$

In Figure 4.5(b), the harmonic voltage $V_h(x)$ can be expressed as

$$\begin{aligned} V_h(x) &= V_{B,h}(x_{bus}) + \int_{x_{bus}}^{x} dV_h(y)dy \\ &= \frac{H_{C,h}}{N_F}\cdot h \cdot Z_{\mathbf{max}} \cdot \left[N_F \cdot x_{bus} + \left(\frac{x^2 - x_{bus}^2}{2(x_{bus}-1)} - \frac{x - x_{bus}}{x_{bus}-1} \right) \right] \end{aligned} \tag{4.9}$$

From the relationship between the system harmonic absorption capacity and the number of feeders, Equation (4.9) can be rewritten as

$$H_{C,h} = \frac{V_{W,h} \cdot N_F}{Z_{max,h} \cdot \left[N_F \cdot x_{bus} + \left(\dfrac{1 - x_{bus}}{2} \right) \right]} \tag{4.10}$$

Equation (4.10) shows that there is a strong relationship between the emission limits and the number of feeders. Therefore, IEEE Std. 519 should have the function to control the emission limits according to the number of feeders in order to guarantee *Rule II* in the weak system.

In the same way, the results of voltage distortions according to the feeder number are shown in Figure 4.6. In accordance with Equation (4.10), the worst resulting voltage distortion is inversely proportional to the feeder number, since increasing the feeder number makes the system stronger. From this, this dissertation clearly shows that IEEE Std. 519 should have a function to control the emission limits according to the number of feeders in order to avoid the violation of *Rule II.*

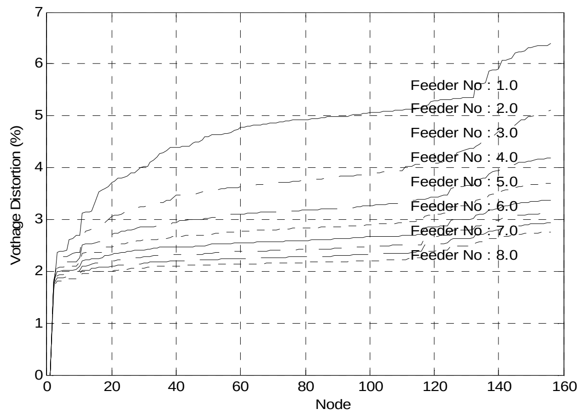


Figure 4.6 : Representative trends of voltage distortions according to the number of feeders

The results of the new emission limits, modified by the correction factor, are shown in Figure 4.7. Figure 4.7 shows the improved trends of the voltage distortions, compared to Figure 4.6. The range of the voltage discrepancy is significantly narrowed down, up to 0.5%, regardless of the number of feeders.

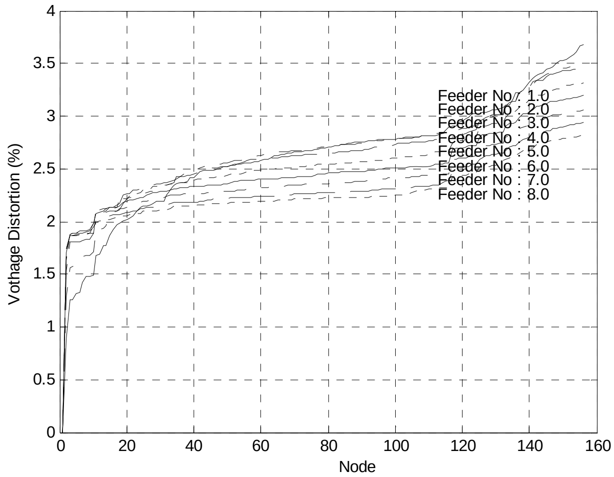


Figure 4.7 : Representative trends of voltage distortions modified by the correction factor of feeder numbers

4.4.3 System Voltage Levels

Although IEEE Std. 519 considers the system voltage level through the short-circuit ratio, it does not fully consider the influence of the system voltage level, as shown in Figure 4.8. This leads to the worst voltage distortions, being far more or less than the planning level according to the variation of the system voltage level.

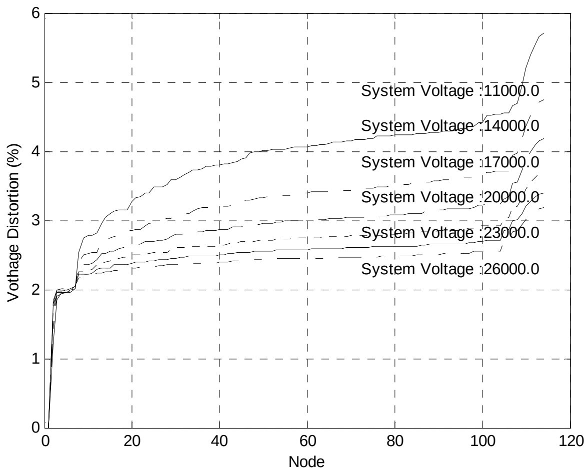


Figure 4.8 : Representative trends of voltage distortions according to system voltage levels

Figure 4.9 shows the results generated by the new emission limits, modified by the correction factor of the system voltage level. Although there are still violations of *Rule II*, the trends of the resulting voltage distortions are improved, compared to Figure 4.8. The range of the voltage discrepancy is significantly narrowed down, up to 0.3%, regardless of the system voltage level.

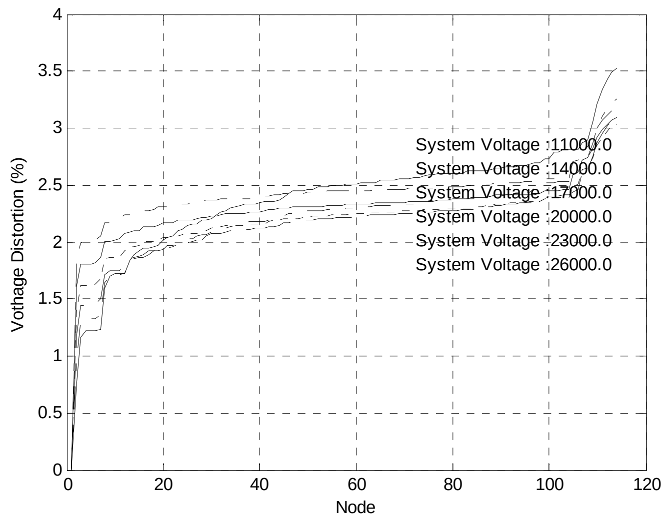


Figure 4.9 : Representative trends of voltage distortions modified by the correction factor of system voltage levels

4.4.4 Total Correction Factor

Three sets of correction factors used to compensate for the influences of three uncertainties of distribution systems are shown in Table 4.6.

Table 4.6 : Correction factors for three uncertainties of distribution systems

Supply capacities		Number of feeders		System voltage level	
Step(v)	$F_{P,h}$	Step(v)	$F_{F,h}$	Step(v)	$F_{V,h}$
10	3.323	1	0.549	11,000	0.62
20	1.753	2	0.727	14,000	0.68
30	1.206	3	0.835	17,000	0.74
40	0.936	4	0.900	20,000	0.82
50	0.778	5	0.945	23,000	0.91
60	0.673	6	0.978	26,000	1.00
70	0.597	7	1.000	29,000	1.09
80	0.542	8	1.016	32,000	1.19

By combining the three correction factors proposed, the total correction factor can be simply defined as

$$F_{T,h} = F_{P,h} \cdot F_{F,h} \cdot F_{V,h} \tag{4.11}$$

where $F_{P,h}$, $F_{F,h}$ and $F_{V,h}$ are the correction factors for the supply capacity, multi-feeders and system voltage levels, respectively.

An example of an application of the approach is presented for assessing the emission limits of IEEE Std. 519, modified by the total correction factor. A 14kV distribution system with a 60MVA supply capacity supplies three feeders with characteristics based on Table 4.2. The comparison of the trends of the voltage distortions generated by the emission limits and modified emission limits of IEEE Std. 519 are shown in Figure 4.10. By applying the total correction factor, the worst voltage has been lowered down from 7% to 3%, which is equal to the planning level. Figure 4.10 clearly shows the excellent feature of the total correction factor.

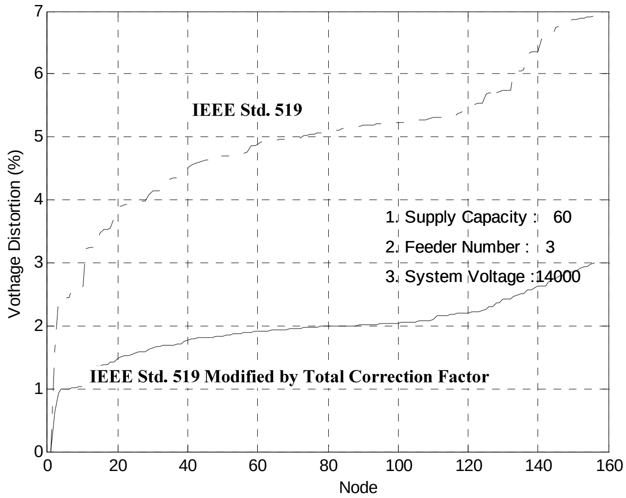


Figure 4.10 : Comparison of the representative voltage distortions evaluated by the IEEE Std. 519 and modified IEEE Std. 519

4.5 Conclusions

This dissertation has proposed how to apply the stochastic method to IEEE Std. 519 and three correction factors to improve the harmonic current emission limits of IEEE Std. 519 in MV systems.

This dissertation has proposed the necessity that IEEE Std. 519 should adopt the stochastic method in IEC 61000-3-6 instead of the deterministic method. This dissertation also shows that IEEE Std. 519 yields very improved results through the general summation law, which is developed based on the Monte-Carlo approach, considering that the compatibility level has to be met with a probability of 95% or better.

Moreover, this dissertation has proved that the universal pre-calculated harmonic current emission limits often lead IEEE Std. 519 to boost voltage distortions theoretically up to twice beyond the planning levels, since it does not fully consider the precarious nature of distribution systems.

To consider the influences of the random nature of distribution systems on the emission limits of IEEE Std. 519, three correction factors have been proposed. In addition, by combining three correction factors, the total correction factor is presented.

The feasibility of the proposed correction factors have been obviously proved, based on the multi-feeder model of distribution systems with the Monte-Carlo method.

CHAPTER 5

Allocation of Global Contribution Limits to HV-EHV Systems in Accordance with the Principles of IEC/TR 61000-3-6

The objective of this chapter is to propose a method for sharing the common HV-EHV planning levels between the different substations or busbars in the supply system (referred to as a global contribution) in accordance with the principles of IEC 61000-3-6[1]. IEC 61000-3-6 is composed of two quite different sets of principles for allocating harmonic emission limits in MV and HV-EHV systems, respectively.

The ultimate goal of IEC 61000-3-6 for HV-EHV systems is to fairly apportion maximum global contribution limits to considered stations under the consideration of the ratio of the power supply to the total power supply capacity of the system while guaranteeing the planning levels. In this chapter, this dissertation analytically investigates the allocation method of the global contribution in IEC 61000-3-6. From the analysis results, this dissertation clearly proves that the major principles applied to IEC 61000-3-6 have problems that should not be ignored, since the solution set often violates the planning level.

To overcome these problems, this chapter proposes a new method that fairly apportions the global contribution limit to each busbar while guaranteeing the planning levels in HV-EHV systems. The feasibility of the proposed method has been clearly demonstrated by guaranteeing that the worst resulting voltage distortions derived from the proposed method are equal to the given planning level, regardless of system structures and circumstances.

5.1 Introduction

In recent years, it has been one of the major concerns for utilities to allocate harmonic emission limits to HV-EHV customers of electronic high-speed trains, as well as high-voltage direct-currents (HVDC) and wind power generators, which generate considerable harmonic currents to HV-EHV systems. To limit actual harmonic voltages to a specific voltage distortion level, the necessity of harmonic standards significantly grows with an emphasis on smart grid (SM) technology.

The utility is responsible for the overall coordination of harmonic levels under normal operating conditions in accordance with national requirements. The customers connected to HV-EHV systems are responsible for maintaining their own harmonic emissions at the point of evaluation (POE) [1] below the global contribution limit specified by the utility.

The significant feature of HV-EHV customers is the limited number of customers having a huge size of agreed power, compared to MV customers. Therefore, the utilities tend to assess compliance with HV-EHV customers more carefully, since their impacts on the power systems are considerable. For over the past two decades, IEC 61000-3-6 has been well known as a harmonic guideline, along with IEEE Std. 519 [2]. However, this has not been applied well to real systems, due to the vagueness of the major principles regarding HV-EHV systems.

Like the principles of MV systems, the ultimate goal of the principles of IEC 61000-3-6 for HV-EHV systems is to limit the actual harmonic voltages on a supply system to a specific level (referred to as a planning level) so that they will not result in adverse effects on equipment connected to LV systems. To allocate harmonic emission limits, IEC 61000-3-6 introduces the concept of the global contribution for sharing the planning level. Among the principles regarding the global contribution applied to IEC 61000-3-6, the stepping stone is the influence coefficient in [1]. However, some serious problems are found in the principles regarding the application of the influence coefficient, as this dissertation will show in section 5.3 of this chapter.

These problems often cause a violation in the planning level when injecting the current emission limits in accordance with the global contribution limits derived from the proposed method. Additionally, the global contribution cannot often be fairly allocated according to the power supply capacity. Note that no research can be found on the investigation of the principles regarding the global contribution method for HV-EHV systems applied in IEC 61000-3-6. Only one study has been carried out on the global contribution for HV-EHV systems [62].

To overcome these shortcomings, a new method is proposed, based on the following new concepts: a) the direct path; b) the total global contribution; c) the reference harmonic voltage and current; d) the reference harmonic global contribution; and e) the allocation constant. The feasibility of the proposed method is clearly demonstrated with calculation examples. The proposed method strongly supports IEC 61000-3-6 and adds to its value.

This chapter is organized into six sections. Sections 5.1 and 5.2 provide the introduction and basic concepts of the allocation principle in IEC 61000-3-6, respectively. Section 5.3 presents the problem formulation. Sections 5.4 and 5.5 show the proposed method and its effectiveness, respectively. Conclusions are drawn in Section 5.6.

5.2 Basic Concepts

To calculate the propagation of harmonic currents with the current injection method, the system impedance matrix is needed. Traditionally, the network relationship can be represented by an admittance or impedance matrix. This dissertation uses the system impedance matrix instead of the admittance matrix in order to avoid the time-consuming inversion of the matrix in Equation (2.1).

5.2.1 Global Contribution

The global contribution defined in IEC 61000-3-6 is the resulting voltage at each busbar, excluding the impacts of all harmonic current excitations, except its own. The definition of the global contribution can be written as

$$\begin{aligned}\lfloor \mathbf{G_{h,B}} \rfloor &= [\mathbf{V_h}] - ([\mathbf{Z_h}] - \mathbf{Dg}([\mathbf{Z_h}])) \cdot [\mathbf{I_h}] \\ &= \mathbf{Dg}([\mathbf{Z_h}]) \cdot [\mathbf{I_h}]\end{aligned} \tag{5.1}$$

$$\begin{bmatrix} G_{h,B1} \\ G_{h,B2} \\ \vdots \\ G_{h,Bn} \end{bmatrix} = \begin{bmatrix} Z_{h,11} & 0 & \cdots & 0 \\ 0 & Z_{h,22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_{h,nn} \end{bmatrix} \begin{bmatrix} I_{h,B1} \\ I_{h,B2} \\ \vdots \\ I_{h,Bn} \end{bmatrix} \tag{5.2}$$

5.2.2 Individual Voltage Emission Limits

Once determining the set of global contributions, individual harmonic voltage emission limits can be obtained by using the same allocation method of the MV system in IEC 61000-3-6. At each harmonic order h, each distorting installation "i" will be allowed a contribution (E_{Uhi}) to the global contribution of a substation or busbar Bn (G_{hBn}) in the considered HV-EHV system, according to the ratio between its agreed power (S_i) and the total available power (S_{tn}) of substation “n.”

$$E_{Uhi} = G_{hBn} \sqrt[\alpha]{\frac{S_i}{S_{tn}}} \tag{5.3}$$

Then, individual current emission limits can be calculated from individual voltage emission limits. In this chapter, this dissertation does not cover these two limits (individual voltage and current), since both limits can be obtained if the values of the global contribution are determined. This dissertation focuses on the issue of the global contribution.

5.2.3 Current Emission Limits

To guarantee the planning level with Equation (5.2), the allocation method for current emission limits should be correlated with the resulting global contribution at each busbar. As expected, the harmonic current emission limits, based on the set of the global contribution levels, can be written as

$$\mathbf{E}_{\mathbf{IhHV-EHV}} = \left[\mathbf{G}_{\mathbf{h,B}}\right] \cdot \mathrm{diag}\left(\mathbf{Z}_{\mathbf{h}}\right)^{-1} \tag{5.4}$$

5.2.4 General Summation law

IEC 61000-3-6 recommends the general summation law for voltages and currents A:

$$A_h = \left(\sum_{i=1}^{n} (A_{h,i})^{\alpha} \right)^{\frac{1}{\alpha}} \tag{5.5}$$

More detailed explanations of Equation (5.5) can be found in Chapter 1 and 4.

5.2.5 Basic Philosophies for Global Contribution

Before allocating the emission limits to busbars at different HV-EHV substations, IEC 61000-3-6 introduces the basic philosophy for sharing the common HV-EHV planning levels between the different substations or busbars in supply systems. Figure 5.1 illustrates a synthesized HV-EHV system configuration.

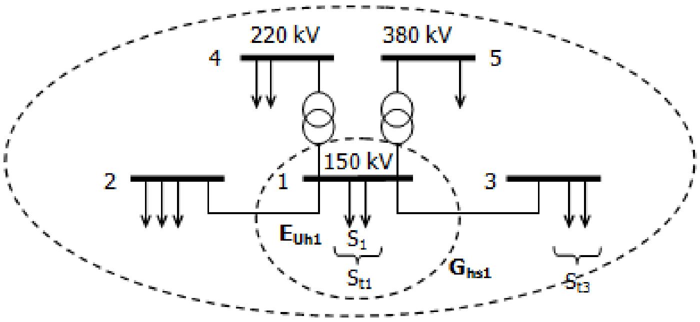


Figure 5.1 : Allocation of global contribution levels to substations in an HV-EHV system

To develop a basic method for evaluating the global contribution, IEC 61000-3-6 defines the basic relationship between the planning level ($L_{hHV\text{-}EHV}$) and the voltage emission level (E_{Uhi}), which is

$$\sqrt[\alpha]{\left(\sum_{i\text{ at }B1} E_{Uhi}{}^{\alpha}\right) + \left(\sum_{i\text{ at }B2} E_{Uhi}{}^{\alpha}\right) + \cdots + \left(\sum_{i\text{ at }Bn} E_{Uhi}{}^{\alpha}\right)} \le L_{hHV-EHV} \tag{5.6a}$$

where $\sum_{i\text{ at }Bn} E_{Uhi}{}^{\alpha} = G_{hBn}{}^{\alpha}$

.

Based on (5.6a), IEC 61000-3-6 presents a principle for the global contribution in accordance with a rule that apportions planning levels between busbars or substations proportionally to their share of the total supply capacity of the given system. The global contribution at busbar "m" is written as

$$G_{h,Bm} \le \sqrt[\alpha]{\frac{S_{tm}}{(S_{t1}) + (S_{t2}) + \cdots + (S_{tn})}} \cdot L_{hHV-EHV} \tag{5.6b}$$

where S_{tn} is the total supply capacity of the substation "n" within the considered system.

5.2.6 General Principles for Global Contribution

To develop a general method for evaluating the global contribution, IEC 61000-3-6 proposes the general relationship between the planning level and the voltage emission level for meshed HV-EHV systems with the application of the influence coefficients between different substations or busbars shown as

$$\begin{pmatrix} K_{h1-m}{}^{\alpha}\left(\sum_{i\text{ at }B1} E_{Uhi}{}^{\alpha}\right) + K_{h2-m}{}^{\alpha}\left(\sum_{i\text{ at }B2} E_{Uhi}{}^{\alpha}\right) + \\ \cdots + K_{hn-m}{}^{\alpha}\left(\sum_{i\text{ at }Bn} E_{Uhi}{}^{\alpha}\right) \end{pmatrix}^{\frac{1}{\alpha}} \le L_{hHV-EHV} \tag{5.7a}$$

where K_{hn-m} is the harmonic voltage of order h, which is caused at node m when a 1 p.u. harmonic voltage is applied at node "n."

Based on the same apportioning principle with (5.6b), the general principle of the global contribution with the influence coefficient is defined as

$$G_{hBm} \leq \sqrt[\alpha]{\frac{S_{tm}}{\left(K_{h1-m}^{\alpha} \cdot S_{t1}\right) + \left(K_{h2-m}^{\alpha} \cdot S_{t2}\right) + \cdots + \left(K_{hn-m}^{\alpha} \cdot S_{tn}\right)}} \cdot L_{hHV-EHV} \tag{5.7b}$$

It is not the purpose of this chapter to discuss IEC 61000-3-6 principles for sharing planning levels. More detailed explanations of these essential concepts can be found in [1].

5.3 Problem Formulation

The primary objective of the harmonic standards is to fairly allocate the current emission limits to each customer according to the agreed power of the customer, while not violating a specific voltage distortion level. Therefore, the harmonic standards for HV-EHV systems should fulfill the following two rules.

Rule I: Fairness

The global contribution limit should be allocated to each busbar, according to the ratio of a given power supply, to the total power supply capacity of the system [1]. This means that the planning levels in the system should be fairly shared with each busbar according to its power supply capacity.

Rule II: Consistency

The harmonic standards should insure a specific voltage distortion level (referred to as the planning level), which will not result in adverse effects on equipment, if all busbars are in compliance with the standard [1, 2].

Practically, it is impossible to analyze the principles of IEC 61000-3-6 for HV-EHV systems due to limited explanations about its own allocation principles. In this chapter, analyses are carried out with the key criteria of whether or not the solution set of the global contribution limits obtained by IEC 61000-3-6 ultimately fulfills *Rules I and II*. In this section, all of the major principles presented in the previous section are verified with analytical methods and calculation examples.

5.3.1 Direct Path

Harmonic standards should be able to allocate the acceptable maximum global contribution, while the voltage distortion level at the weakest busbar is equal to the given planning level in accordance with *Rule II*.

To verify Equation (5.6) of IEC 61000-3-6 principles, the direct path (referred to as "DP" here) is defined herewith. DP is developed here to identify the weakest busbar where the worst voltage distortion is presented. As an example, a system consisting of four sets of DP is shown in Figure 5.2. For simplicity, this dissertation assumes that line impedances between busbars and the total load capacity connected to each busbar are identical. Under these assumptions, the eighth busbar in DP_4 is the weakest among all of the busbars. DP_4 is called the major DP. The set of busbars in the major DP is {B1, B3, B5, B7, B8}.

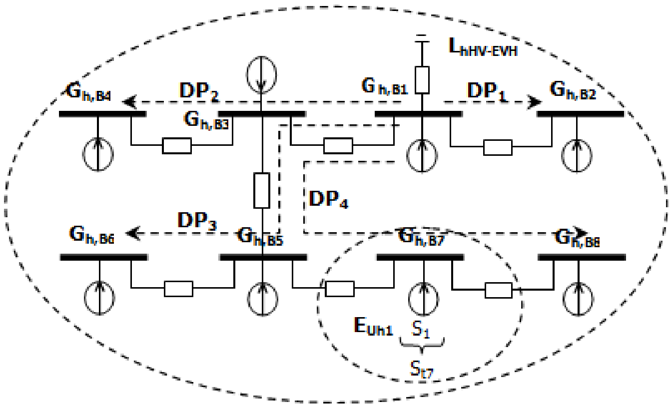


Figure 5.2 : An example with four DPs

5.3.2 Verification of Basic Philosophy

To identify the value of the worst voltage distortion at the weakest busbar with respect to the global contribution limit, the total individual global contribution level at busbar "i" is defined as

$$T_{Gh,Bi} = \left(\sum_{j \text{ at Bus } i} G^{\alpha}_{h,B(ij)} \right)^{\frac{1}{\alpha}} \tag{5.8}$$

where $G_{h,B(ij)} = \dfrac{Z_{h,ii}}{Z_{h,jj}} \cdot G_{h,B(jj)} = C_j \cdot G_{h,Bj}$, $G_{h,B(ii)} = G_{h,Bi}$.

Equation (5.8) explicitly shows that the constant C should be less than one. For an example, $T_{Gh,B1}$ in Figure 5.2 can be obtained as

$$\begin{aligned} T_{Gh,B1} &= \left(\sum_{j \text{ at Bus } 1} G^{\alpha}_{h(1j)} \right)^{\frac{1}{\alpha}} \\ &= \left(G^{\alpha}_{h11} + G^{\alpha}_{h12} \right)^{\frac{1}{\alpha}} \end{aligned} \tag{5.9}$$

The summation of the total global contributions on the major DP is equal to the worst voltage distortion at the weakest busbar. Therefore, the worst voltage distortion in Figure 5.2 can be written as

$$W_{VhHV-EHV} = \left(T^{\alpha}_{Gh,B1} + T^{\alpha}_{Gh,B3} + T^{\alpha}_{Gh,B5} + T^{\alpha}_{Gh,B7} + T^{\alpha}_{Gh,B8}\right)^{\frac{1}{\alpha}} \qquad (5.10)$$

Using Equation (5.8), the total individual global contribution levels with the system relationship matrix between $T_{Gh,B}$ and $G_{h,B}$ shown in Figure 5.2 can be expressed as

$$\begin{bmatrix} T_{Gh,B1} \\ T_{Gh,B3} \\ T_{Gh,B5} \\ T_{Gh,B7} \\ T_{Gh,B8} \end{bmatrix} = \left[\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} G_{h,B11} \\ G_{h,B12} \\ G_{h,B33} \\ G_{h,B34} \\ G_{h,B55} \\ G_{h,B56} \\ G_{h,B77} \\ G_{h,B88} \end{bmatrix}^{*\alpha} \right]^{*\frac{1}{\alpha}} \qquad (5.11)$$

With the application of (5.8), substituting (5.11) into (5.10), (5.10) can be written as

$$W_{VhHV-EHV} = \begin{bmatrix} (C \cdot G^{\alpha}_{h,B11} + C_2 G^{\alpha}_{h,B22}) + (C \cdot G^{\alpha}_{h,B33} + C_4 G^{\alpha}_{h,B44}) + \\ (C \cdot G^{\alpha}_{h,B55} + C_6 G^{\alpha}_{h,B66}) + C \cdot G^{\alpha}_{h,B77} + C \cdot G^{\alpha}_{h,B88} \end{bmatrix}^{*\frac{1}{\alpha}} \qquad (5.12)$$

where the constant C is 1, and the other constants are less than one, in accordance with (5.8).

If the global contribution limits are fairly allocated while satisfying *Rules I* and *II*, the value of the worst voltage distortion is equal to the planning level. Therefore, (5.12) can be rewritten as

$$\begin{aligned}
L_{hHV-EHV} &= \sqrt[\alpha]{C_1\left(\sum_{i\,at\,B\,1} E_{Uhi}{}^{\alpha}\right)+C_2\left(\sum_{i\,at\,B\,2} E_{Uhi}{}^{\alpha}\right)+\cdots+C_n\left(\sum_{i\,at\,B\,n} E_{Uhi}{}^{\alpha}\right)} \\
&\le \sqrt[\alpha]{\left(\sum_{i\,at\,B\,1} E_{Uhi}{}^{\alpha}\right)+\left(\sum_{i\,at\,B\,2} E_{Uhi}{}^{\alpha}\right)+\cdots+\left(\sum_{i\,at\,B\,n} E_{Uhi}{}^{\alpha}\right)} \\
&= C\cdot\sqrt[\alpha]{\left(\sum_{i\,at\,B\,1} E_{Uhi}{}^{\alpha}\right)+\left(\sum_{i\,at\,B\,2} E_{Uhi}{}^{\alpha}\right)+\cdots+\left(\sum_{i\,at\,B\,n} E_{Uhi}{}^{\alpha}\right)}
\end{aligned} \tag{5.13}$$

where the constant C is less than 1.

With Equation (5.13), this dissertation clearly proves that the basic principle of (5.6a) is no longer valid. Equation (5.6a) should be corrected as (5.13). With the application of (5.13), this dissertation proves that the principle of (5.6b) should also be corrected. In the strict sense, (5.6b) can be written as

$$G_{h,Bm} = L_{hHV-EHV} \cdot \left(\frac{S_m}{S_t}\right)^{\frac{1}{\alpha}} \tag{5.14a}$$

where $S_t = S_{t1} + S_{t2} + \cdots + S_{tn}$.

In a system with “n” busbars, (5.14a) can be generally expressed as

$$\left[\mathbf{G_{h,B}}\right]=L_{hHV-EHV}\cdot\begin{bmatrix}\frac{S_1}{S_t}\\ \frac{S_2}{S_t}\\ \vdots\\ \frac{S_n}{S_t}\end{bmatrix}^{\frac{1}{\alpha}} \tag{5.14b}$$

Equation (5.14b) should be fulfilled as

$$\begin{aligned}\left(G^{\alpha}_{h,B1}+G^{\alpha}_{h,B2}+\cdots+G^{\alpha}_{h,Bn}\right)^{\frac{1}{\alpha}} &= L_{hHV-EHV}\cdot\left(\frac{S_1}{S_t}+\frac{S_2}{S_t}+\cdots+\frac{S_n}{S_t}\right)\\ &= L_{hHV-EHV}\end{aligned} \tag{5.15a}$$

Equation (5.13c) can be clearly rewritten as

$$L_{hHV-EHV}=C\cdot\left(G^{\alpha}_{h,B1}+G^{\alpha}_{h,B2}+\cdots+G^{\alpha}_{h,Bn}\right)^{\frac{1}{\alpha}} \tag{5.15b}$$

By simply comparing (5.15a) and (5.15b), (5.6b) is completely invalid. In order to be consistent with (5.13), the general form (5.15a) should be corrected as

$$\left[\mathbf{G_{h,B}}\right]=C_h\cdot L_{hHV-EHV}\cdot\begin{bmatrix}\frac{S_1}{S_t}\\ \frac{S_2}{S_t}\\ \vdots\\ \frac{S_n}{S_t}\end{bmatrix}^{\frac{1}{\alpha}} \tag{5.16a}$$

or, as a final result

$$G_{h,Bi} = C_h \cdot L_{hHV-EHV} \cdot \left(\frac{S_i}{S_t} \right)^{\frac{1}{\alpha}} \tag{5.16b}$$

where C_h is a constant.

From (5.14) – (5.16), (5.6b) should be corrected as

$$G_{h,Bm} = C_h \cdot L_{hHV-EHV} \cdot \sqrt[\alpha]{\frac{S_{tm}}{(S_{t1}) + (S_{t2}) + \cdots + (S_{tn})}} \tag{5.16c}$$

5.3.3 Verification for General Principles

From the problems in (5.6), we can assume that the general principle of (5.7) for meshed systems may have some problems, since (5.7) is built on (5.6) with the application of the influence coefficient. The influence coefficient K_{hn-m} is the harmonic voltage of order h, which is caused at node “m” when a 1 p.u. harmonic voltage of order h is applied at node “n.” Unlike the basic principle (6), it is not trivial to analytically verify the general methods applied to IEC 61000-3-6 because of the complexity of the influence coefficient.

Therefore, the verification of the general principles is carried out by investigating whether or not the solution set evaluated by the general principles can guarantee *Rules I and II*. In order to prove whether or not the general methods can guarantee *Rule I*, I choose the identical values of the power supply capacities (S_{tn}), as shown in Table 5.2. In this case, the solutions of the global contributions should be identical in accordance with

Rule I. Then, I inject the solution set of the current emission limits according to the obtained global contribution limits. In this case, the resulting worst voltage at the weakest busbar should be exactly equal to a given planning level, in accordance with *Rule II*.

A case study example for investigating the principle (5.7) is shown in Figure 5.3. For simplicity, the source reactance at busbar 1 is 0.01 p.u., and the seven line impedances (0.06 p.u.) are identical, and the given planning level is 2%. Only the 5^{th} harmonic is focused on throughout this chapter with the following assumptions:

- The power system consists of linear devices.
- The linear model is used (inductive reactance is proportional to the frequency and capacitive reactance is inversely proportional to the frequency).

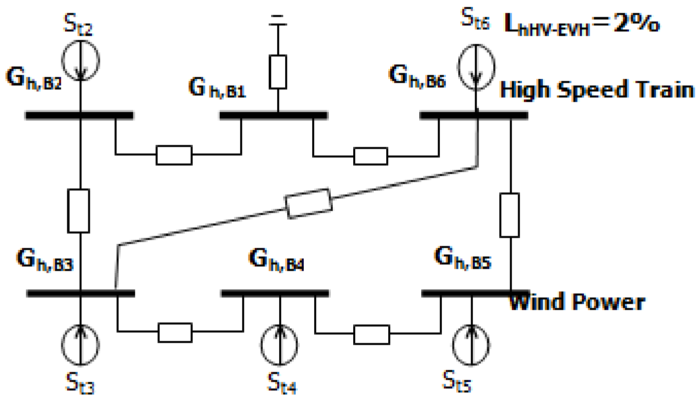


Figure 5.3 : An example for investigating the general principles of IEC 61000-3-6

The evaluation results, according to the general principles applied to IEC 61000-3-6 and the proposed method, are shown in Table 5.1. Table 5.1 clearly proves that the IEC 61000-3-6 principles cannot guarantee the planning level, since the worst voltage violates the planning level. In other words, the general principles (5.7) cannot fulfill *Rule*

II. In contrast, the worst voltage, according to the proposed method, which will be introduced the next section, is exactly equal to the planning level 2%.

Table 5.1 : Solution sets based on the method in IEC 61000-3-6

	Stm(p.u.)	DPI(p.u)[1)]	IEC 61000-3-6		Proposed method	
			$G_{h,Bm}$	$V_{h,Bm}$	$G_{h,Bm}$	$V_{h,Bm}$
Busbar 2	0.20	0.55	0.62	1.70	0.47	1.52
Busbar 3	0.15	0.70	0.42	1.98	0.38	1.80
Busbar 4	0.50	0.75	0.90	2.18	0.90	2.00
Busbar 5	0.28	0.70	0.61	2.14	0.60	1.96
Busbar 6	0.70	0.55	1.29	1.96	1.15	1.78

1) Driving point harmonic impedance.

In addition, to prove whether or not the general principles can guarantee *Rule I*, I reset the values of the power supply capacity (S_{tn}) in Table 5.1 into the same values, as shown in Table 5.2. Table 5.2 clearly demonstrates that there are some problems in (5.7), since the IEC 61000-3-6 principles cannot guarantee *Rule I*. However, the identical solution set of the global contributions obviously proves that the proposed method can guarantee *Rule I*.

Table 5.2 : Solution sets based on the method in IEC 61000-3-6

	S_{tm}(p.u.)	DPI(p.u)	IEC 61000-3-6		Proposed method	
			$G_{h,Bm}$ [1)]	$V_{h,Bm}$	$G_{h,Bm}$ [2)]	$V_{h,Bm}$
Busbar 2	0.50	0.55	0.73	2.08	0.62	1.71
Busbar 3	0.50	0.70	0.65	2.29	0.62	1.93
Busbar 4	0.50	0.75	0.63	2.36	0.62	2.00
Busbar 5	0.50	0.70	0.65	2.29	0.62	1.93
Busbar 6	0.50	0.55	0.73	2.08	0.62	1.71

1) The values of the solution set are different.
2) The values of the solution set are exactly identical.

In this section, this dissertation clearly demonstrates that the general principle (5.7) clearly cannot guarantee *Rules I* and *II* with a simple, but very intuitive example.

5.4 Proposed Method

In this section, this dissertation introduces the proposed method developed, based on the following new concepts: a) the reference harmonic voltage set; b) the reference harmonic current set; and c) the reference harmonic global contribution set. The proposed method is developed in accordance with both *Rules I* and *II*.

5.4.1 Decomposition

By using (5.5), the unknown harmonic voltage vector under consideration of the stochastic method applied in [1] can be expressed as

$$[\mathbf{V_h}] = \left([\mathbf{Z_h}]^{*\alpha} \cdot [\mathbf{I_h}]^{*\alpha}\right)^{*\frac{1}{\alpha}} \tag{5.17}$$

where α is an exponent.

With the definition of the global contribution in (5.1), (5.17) can be decomposed as

$$\begin{aligned} [\mathbf{V_h}] &= \left([\mathbf{Z_h}]^{*\alpha} \cdot \left(\mathbf{Dg}([\mathbf{Z_h}])^{-1}\right)^{*\alpha} \cdot \mathbf{Dg}([\mathbf{Z_h}])^{*\alpha} \cdot [\mathbf{I_h}]^{*\alpha}\right)^{*\frac{1}{\alpha}} \\ &= \left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{G_h}]^{*\alpha}\right)^{*\frac{1}{\alpha}} \end{aligned} \tag{5.18}$$

where K_h (referred to as the system coefficient matrix here) is $[\mathbf{Z_h}] \cdot \mathbf{Dg}([\mathbf{Z_h}])^{-1}$.

Substituting (5.16) into (5.18), (5.18) becomes

$$
\begin{aligned}
[\mathbf{V_h}] &= \left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{G_h}]^{*\alpha}\right)^{*\frac{1}{\alpha}} \\
&= \left([\mathbf{K_h}]^{*\alpha} \cdot \left(\mathrm{C_h} \cdot \mathrm{L_{hHV-EHV}} [\mathbf{S}]^{*\frac{1}{\alpha}} \right)^{*\alpha} \right)^{*\frac{1}{\alpha}} \\
&= \left(\mathrm{C_h} \cdot \mathrm{L_{hHV-EHV}}\right) \cdot \left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{S}]\right)^{*\frac{1}{\alpha}} \\
&= \mathrm{C_h} \cdot \left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{S}]\right)^{*\frac{1}{\alpha}}
\end{aligned}
\tag{5.19}
$$

where $\mathrm{C_h}$ is the allocation constant.

5.4.2 Reference Harmonic Voltage

From (5.19), a reference harmonic voltage response set (referred to as "$\mathrm{R_{Vh}}$" here), is defined as

$$
[\mathbf{R_{Vh}}] = \left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{S}]\right)^{*\frac{1}{\alpha}} \tag{5.20a}
$$

With the application of the influence coefficient presented in IEC 61000-3-6, (5.20a) can be expressed as (5.20b) and (5.20c).

$$
\mathrm{R_{Vh,Bm}} = \left((\mathrm{K^{\alpha}_{h,1-m}} \cdot \mathrm{S_{t1}}) + (\mathrm{K^{\alpha}_{h,2-m}} \cdot \mathrm{S_{t2}}) + \cdots + (\mathrm{K^{\alpha}_{h,n-m}} \cdot \mathrm{S_{tn}})\right)^{*\frac{1}{\alpha}} \tag{5.20b}
$$

$$
\begin{bmatrix} \mathrm{R_{Vh,B1}} \\ \mathrm{R_{Vh,B2}} \\ \vdots \\ \mathrm{R_{Vh,Bn}} \end{bmatrix} = \begin{bmatrix} \left(\mathrm{S_{t1}} + (\mathrm{K^{\alpha}_{h,2-1}} \cdot \mathrm{S_{t2}}) + \cdots + (\mathrm{K^{\alpha}_{h,n-1}} \cdot \mathrm{S_{tn}})\right) \\ \left((\mathrm{K^{\alpha}_{h,1-2}} \cdot \mathrm{S_{t1}}) + \mathrm{S_{t2}} + \cdots + (\mathrm{K^{\alpha}_{h,n-2}} \cdot \mathrm{S_{tn}})\right) \\ \vdots \\ \left((\mathrm{K^{\alpha}_{h,1-n}} \cdot \mathrm{S_{t1}}) + (\mathrm{K^{\alpha}_{h,2-n}} \cdot \mathrm{S_{t2}}) + \cdots + \mathrm{S_{tn}}\right) \end{bmatrix}^{*\frac{1}{\alpha}} \tag{5.20c}
$$

where $K_{hi-i} = \frac{Z_{hii}}{Z_{hii}}$.

5.4.3 Reference Harmonic Current

this dissertation defines the concept of a reference harmonic current injection set (referred to as "R_{Ih}" here). From (5.17), the building method of the reference harmonic current injection set R_{Ih} can be written as

$$\begin{aligned}
[\mathbf{R_{Ih}}] &= \left(\left([\mathbf{Z_h}]^{*\alpha} \right)^{-1} \cdot [\mathbf{R_{Vh}}]^{*\alpha} \right)^{*\frac{1}{\alpha}} \\
&= \left(\left([\mathbf{Z_h}]^{*\alpha} \right)^{-1} \cdot \left[\left([\mathbf{K_h}]^{*\alpha} \cdot [\mathbf{S}] \right)^{*\frac{1}{\alpha}} \right]^{*\alpha} \right)^{*\frac{1}{\alpha}} \\
&= \left(\left([\mathbf{Z_h}]^{*\alpha} \right)^{-1} \cdot \left(\left[[\mathbf{Z_h}] \cdot \mathbf{Dg}([\mathbf{Z_h}])^{-1} \right]^{*\alpha} \cdot [\mathbf{S}] \right) \right)^{*\frac{1}{\alpha}} \\
&= \mathbf{Dg}([\mathbf{Z_h}])^{-1} [\mathbf{S}]^{*\frac{1}{\alpha}}
\end{aligned} \tag{5.21a}$$

With "n" busbar systems, the expanded form of (5.21a) is expressed as

$$
\begin{bmatrix} R_{Ih,1} \\ R_{Ih,2} \\ \vdots \\ R_{Ih,n} \end{bmatrix} = \left(\left(\begin{bmatrix} Z_{h,11} & Z_{h,12} & \cdots & Z_{h,1n} \\ Z_{h,21} & Z_{h,22} & \cdots & Z_{h,2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{h,n1} & Z_{h,n2} & \cdots & Z_{h,nn} \end{bmatrix}^{*\alpha} \right)^{-1} \cdot \begin{bmatrix} R_{Vh,1} \\ R_{Vh,2} \\ \vdots \\ R_{Vh,n} \end{bmatrix}^{*\alpha} \right)^{*\frac{1}{\alpha}}
$$

$$
= \begin{bmatrix} \frac{1}{Z_{h,11}} & 0 & \cdots & 0 \\ 0 & \frac{1}{Z_{h,22}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{Z_{h,nn}} \end{bmatrix} \begin{bmatrix} S_{t1} \\ S_{t2} \\ \vdots \\ S_{tn} \end{bmatrix}^{*\frac{1}{\alpha}} \tag{5.21b}
$$

5.4.4 Reference Global Contribution

This dissertation defines the reference global contribution set (referred to as "R_{Gh}" here). The solution set of the global contribution limits exists on the span of the R_{Gh}. From (5.2) and (5.17), the reference global contribution set is defined as

$$
\begin{aligned}
[\mathbf{R_{Gh,B}}] &= \left([\mathbf{R_{Vh,B}}]^{*\alpha} - \left(([\mathbf{Z_h}] - \mathbf{Dg}([\mathbf{Z_h}]))^{*\alpha} \right) \cdot [\mathbf{R_{Ih,B}}]^{*\alpha} \right)^{*\frac{1}{\alpha}} \\
&= \left(\mathbf{Dg}([\mathbf{Z_h}])^{*\alpha} \cdot [\mathbf{R_{Ih,B}}]^{*\alpha} \right)^{*\frac{1}{\alpha}} \\
&= \left(\mathbf{Dg}([\mathbf{Z_h}])^{*\alpha} \cdot \left(\mathbf{Dg}([\mathbf{Z_h}])^{-1} \cdot [\mathbf{S}]^{*\frac{1}{\alpha}} \right)^{*\alpha} \right)^{*\frac{1}{\alpha}}
\end{aligned} \tag{5.22a}
$$

Then, the expanded form of (5.22a) can be rewritten as

$$\begin{bmatrix} R_{Gh,B1} \\ R_{Gh,B2} \\ \vdots \\ R_{Gh,Bn} \end{bmatrix} = \left(\begin{bmatrix} Z_{h,11} & 0 & \cdots & 0 \\ 0 & Z_{h,22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Z_{h,nn} \end{bmatrix}^{*\alpha} \cdot \left(\begin{bmatrix} \frac{1}{Z_{h,11}} & 0 & \cdots & 0 \\ 0 & \frac{1}{Z_{h,22}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1}{Z_{h,nn}} \end{bmatrix} \begin{bmatrix} S_{t1} \\ S_{t2} \\ \vdots \\ S_{tn} \end{bmatrix}^{*\frac{1}{\alpha}} \right)^{*\alpha} \right)^{*\frac{1}{\alpha}} \tag{5.22b}$$

5.4.5 Global Contribution

From (5.22), the global contributions can be obtained as

$$\lfloor \mathbf{G_{h,B}} \rfloor = C_h \cdot [\mathbf{R_{Gh}}] \tag{5.23}$$

5.5 Applications

To demonstrate the feasibility of the proposed method, this dissertation carries out calculation examples, as shown in Figure 5.4, which illustrates all of the proposed principles presented in section 5.4. To check whether all of the resulting voltages satisfy *Rule II*, the set of the voltage distortions is calculated on the stochastic current injection method in accordance with (5.5). A case for dealing with the effect of capacitor banks within the system, which may cause parallel resonance to a specific harmonic order, can be considered when the capacitor bank at busbar 7 is switched on. For simplicity, the aim of this example is focused on obtaining the global contribution limit for the 5th harmonic. In calculating the emission limits, it is recommended to take into account not only the existing installations, but also new installations that could be connected to the system in the future. In this example, the network is considered to be fully loaded. The addition of new installations to the network will call for changes in the system that are not considered. In considering HV-EHV systems, customers may be connected at different voltage levels so that this dissertation uses the per-unit basis.

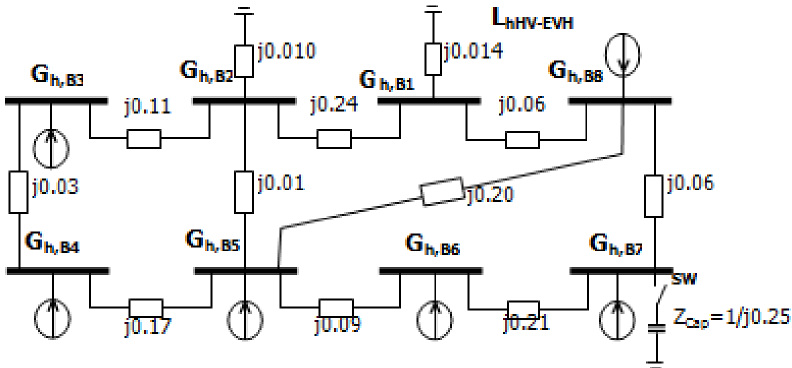


Figure 5.4 : Per-unit equivalent circuit in HV-EHV systems

The evaluation results are shown in Table 5.3. In Table 5.3, when the capacitor bank at busbar 7 is switched off, busbar 6 is the weakest, and the worst voltage at this busbar is exactly equal to the planning level 2%. In the case of switching on the capacitor, the weakest busbar is not changed, and the worst voltage is also exactly identical with the given planning level. These results clearly prove that the proposed method can guarantee the planning level, regardless of the system structures, since the worst voltage does not violate the planning level. In other words, the proposed method fulfills *Rule II*.

Table 5.3 : Allocation results of the global contributions (I)

	S_{tn}(p.u)	DPI (p.u.)		SW OFF		SW ON	
		SW OFF	SW ON	$G_{h,Bm}$	$V_{h,Bm}$	$G_{h,Bm}$	$V_{h,Bm}$
Busbar 3	0.70	0.40	0.41	1.152	1.826	1.112	1.763
Busbar 4	0.50	0.43	0.44	0.906	1.841	0.874	1.795
Busbar 5	0.30	0.07	0.09	0.629	0.859	0.607	0.919
Busbar 6	1.00	0.38	0.42	1.486	2.000	1.434	2.000
Busbar 7	0.50	0.34	0.44	0.906	1.835	0.874	1.903
Busbar 8	0.70	0.34	0.25	1.152	1.570	1.112	1.533

In addition, to prove that the proposed method guarantees *Rule I*, this dissertation changes the values of the power supply capacities (S_{tn}) in Table 5.3 into the same values as shown in Table 5.4. According to *Rule I*, the resulting global contributions at all of the busbars should be identical.

The sets of the global contributions, according to the proposed method, with and without the capacitor, are shown in Table 5.4. From the identical values of the global contributions, regardless of system circumstances, this dissertation obviously demonstrates that the proposed method also guarantees *Rule I*.

Table 5.4 : Allocation results of the global contributions (II)

	S_{tn}(p.u)	DPI (p.u.)		SW OFF		SW ON	
		SW OFF	SW ON	$G_{h,Bm}$	$V_{h,Bm}$	$G_{h,Bm}$	$V_{h,Bm}$
Busbar 3	0.30	0.40	0.41	1.012	1.936	1.014	1.914
Busbar 4	0.30	0.43	0.44	1.012	2.000	1.014	2.000
Busbar 5	0.30	0.07	0.09	1.012	1.172	1.014	1.243
Busbar 6	0.30	0.38	0.42	1.012	1.800	1.014	1.888
Busbar 7	0.30	0.34	0.44	1.012	1.814	1.014	1.958
Busbar 8	0.30	0.34	0.25	1.012	1.488	1.014	1.530

In this section, this dissertation clearly demonstrates that the proposed method guarantees *Rules I* and *II* with a simple, but very intuitive example.

5.6 Conclusions

In order to allocate harmonic emission limits in HV-EHV systems, two major methodologies in IEC 61000-3-6 have been investigated to see whether they are accurate and general enough for all situations. The idea of the first methodology is that when all individual users are injecting up to their emission limits, the summation of all global contributions should be equal to or less than the planning levels in radial HV-EHV systems.

To investigate this methodology, new concepts of direct path (DP) and the total global contribution have been developed to obtain the total voltage drop along the route from the source to the far endpoint and to find the unknown participation factor, respectively. Based on the proposed concepts, the inaccuracy of the first methodology has been investigated analytically, and we have shown that the first methodology in IEC 61000-3-6 is only valid when a network topology is a simple line without lateral.

To investigate the second methodology for sharing planning levels in meshed HV-EHV systems, a new procedure has been developed based on the following concepts: a) the allocation constant, b) the reference harmonic voltage set, and c) the reference harmonic current set. The proposed procedure has been investigated through a number of examples with the direct system impedance matrix. Evaluation results based on the proposed method have demonstrated that the second methodology is not appropriate, since an inconsistency would allow the voltage distortion limits to go beyond the planning level.

To overcome those problems, a new method for allocating harmonic emission limits in HV-EHV systems has been developed based on the reference harmonic global contribution set. The solutions derived by the proposed method have demonstrated better performance than the two in IEC 61000-3-6 since the solutions derived by the proposed method are more accurate.

The effectiveness of the proposed method has been investigated by demonstrating that the resulting value of the worst voltage distortion in the system is exactly the same as the planning voltage level. Moreover, the proposed method can be applied in resonance situations without any additional method.

IEC 61000-3-6 should be accurate and consistent in limiting harmonic voltages in HV-EHV systems, since it has been well known as a harmonic guideline along with IEEE Std. 519 for the past two decades. The proposed method is in compliance with IEC 61000-3-6 and can greatly improve it. In addition, it could help the utilities allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently with the aid of DAS.

CHAPTER 6

Identifying Impacts of Background Voltage Distortions on Harmonic Emission Limits in Accordance with IEC/TR 61000-3-6 for MV Customers

The objective of this chapter is to provide a methodology to identify the effects of the background voltage distortion on a particular MV customer under a harmonic compliance test in accordance with the IEC 61000-3-6 principles. IEC 61000-3-6 and IEEE Std. 519 are well-known harmonic standards that are developed to fairly allocate emission limits to their customers so as not to violate given planning levels without consideration of the background voltage distortion. Therefore, one major difficulty in harmonic standards is how to separate the customer and supply side harmonic contributions from the measured quantity. Customers under compliance tests are often concerned about the effects of background voltage distortions generated by the other customers at the point of evaluation (POE).

To solve this problem, separation methods have been proposed from the viewpoint of the measurement side. This dissertation is the first attempt to approach this problem from the viewpoint of harmonic standards. This dissertation clearly proposes a concrete method of separating contributions generated by a particular customer from other customers connected to the supply system, based on IEC 61000-3-6.

In addition, this dissertation clearly concludes that the impact of background voltage distortion cannot be ignored, since a considerable non-linear current can be generated in accordance with the level of the load impedance and the background voltage distortion at the POE.

6.1 Introduction

The development of technology over years, especially the progress of power electronic applications, has brought about many technical conveniences and economic profits operating at their maximal performance limits; however, it has simultaneously created new challenges for power utility companies, with harmonic distortion being one of them.

This increasing trend represents a concern for planning engineers on utility companies because of the distributed and stochastic nature of these non-linear loads. With the application of distribution automation systems (DAS), power utilities try to predict harmonic distortion levels generated by non-linear loads and evaluate the harmonic absorption capacity of the system in accordance with national regulations or international standards.

To maintain a specific harmonic voltage levels under normal operating conditions, IEC 61000-3-6 and IEEE Std.519 are developed based on the agreed power of the contraction [1, 2].

The major objective of both standards is to allocate the emission limits to their customers so as to prevent the overall system harmonic voltage levels from exceeding the planning levels. Therefore, both standards focus on how to fairly allocate emission limits to each customer under the consideration of the ratio of the customer's size to the total power supply capacity of the system while guaranteeing the planning levels. However, they are not concerned with the impacts of the background voltage distortions.

Although power utilities are responsible for the identification of those contributions, utilities cannot determine whether or not the measured quantity is within acceptable limits because the measured quantity is the result of a combination from all of the other customers, including the customer under compliance assessment.

To overcome this problem, methods have been proposed from the standpoint of the measurement side.

Although an incentive-based scheme was proposed earlier, the main difficulty faced was how to determine the harmonic contributions of the parties involved [3]. The concept of harmful and useful harmonic currents was proposed in [16, 17]. If the injection of a harmonic current at a certain bus causes a decrease in the harmonic voltage at all other buses, it is referred to as a useful harmonic current. A pioneering concept of the separation is developed, based on the conforming and nonconforming concepts [14, 85]. Nevertheless, a problem was found in this concept [86]. The Norton approach was presented for modeling distribution networks, where the system configuration is not fully known [87]. New power quality indices [88] were developed, based on the concept of separation methods [14, 85]. Recently, intelligent methods have been developed to separate customers and supply side contributions [21, 89].

This dissertation is the first attempt to directly approach to this problem from the viewpoint of the harmonic standard side. This chapter is organized into five sections. Sections 6.1 and 6.2 provide the introduction and basic concepts of the separation of the background distortion effects, respectively. Section 6.3 describes the proposed method, while Section 6.4 shows the results of the harmonic emission allocation set under consideration of background distortion. Conclusions are drawn in Section 6.5.

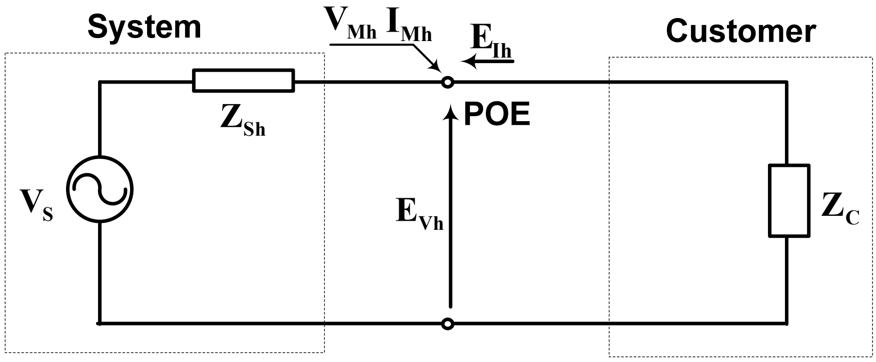
6.2 Basic concepts

Compared to IEEE Std. 519[2], the principles of IEC 61000-3-6[1] can be applied to a wide variety of system conditions at the expense of becoming complex. To separate the customers and the supply side contributions, this dissertation defines a simple, but intuitive concept referred to as an addition and subtraction method here. The basic concepts presented here are directly applied to IEC 61000-3-6 in the next section.

6.2.1 Background Voltage Distortion

The measured current and voltage waveforms combine the effects of the numerous deforming installations connected to the system from all of the other consumers. For simplicity, in case one customer is connected to the supply system, as shown in Figure 6.1, the utilities can assess whether or not the customer's installation is behaving within the emission limits (E_{Ih}) allocated by IEC 61000-3-6. Figure 6.1 introduces the basic concepts of IEC 61000-3-6, which allocate harmonic emission limits.

Compliance assessment can be carried out by simply comparing the value of the emission limits with the measured harmonic current at the POE because of no background voltage distortion in the supply system. Therefore, without the interface of other customers, there is no reason for customers to concern about the background voltage distortion from the supply system.

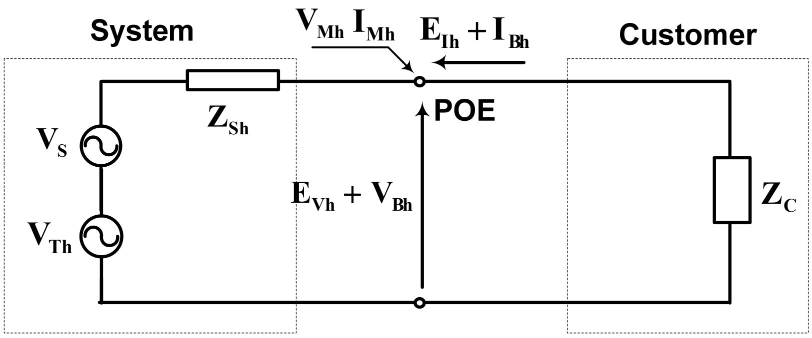


V_S :	Sinusoidal supply system voltage
Z_{Sh}:	Supply system harmonic impedance
Z_C :	Customer's load impedance
V_{Mh}:	Measured harmonic voltage at a POE
I_{Mh}:	Measured harmonic current at a POE
E_{Vh} :	Allocated harmonic voltage emission limit to the customer
E_{Ih}:	Allocated harmonic current emission limit to the customer

Figure 6.1 : IEC 61000-3-6 model for allocating emission limits without the interface of other customers

However, generally many customers are connected to a distribution system so that it is necessary to analyze the influence of the voltage distortion generated by the other customers when assessing compliance. This dissertation defines the term "background voltage distortion" as the voltage at the POE when non-liner sources in the particular customer under the compliance assessment are deactivated. In other words, the background voltage distortion is the voltage generated by the current injections of all the other customers, except for that particular customer.

In Figure 6.2, the harmonic currents injected from the other customers generate the background voltage distortion associated with the system harmonic impedance at the POE. Note that the background voltage distortion is not the same meaning with the conventional term, which can be expressed as the Thevenin equivalent harmonic voltage source [87].



V_{Th} : Thevenin equivalent harmonic voltage

V_{Bh} : Background voltage distortion

I_{Bh} : Background harmonic current

Figure 6.2 : IEC 61000-3-6 model for allocating emission limits with the interface of other customers

6.2.2 Background Current Distortion

From the background voltage distortion, the background harmonic current is defined as the current generated by the background voltage distortion at the POE associated with the load harmonic impedance. In other words, the background current distortion is the current generated by the background voltage distortion, associated with the aggregated load impedance of the customer under the compliance test. To analytically identify the contribution of the background current distortion, we assume that customer's loads consist of two kinds of portions, such as a linear portion and a non-linear portion, in a heuristic sense, as shown in Figure 6.3. This dissertation defines two terms – "a linear portion" and a "non-linear portion" – as the following

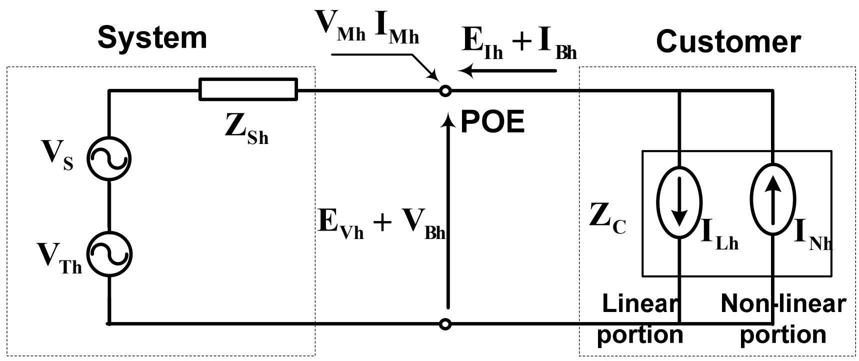
• A linear portion is the one that generates the fundamental current, equal to the fundamental current actually flowing through the POE.

• Any other portion is a non-linear portion that cannot generate the fundamental frequency power.

These terms differ from the classical concept of non-linear loads. In Figure 6.3, the measured current and voltage can be expressed as

$$\begin{aligned} I_M(j\omega_n) &= I_L(jn\omega_1) - I_N(jn\omega_1) \\ &= -\left(E_I(jn\omega_1) + I_B(jn\omega_1)\right) \end{aligned} \tag{6.1}$$

where ω_1 is the fundamental frequency, and ω_n is the h order harmonic frequency.



I_{Lh} : Harmonic current generated by a linear portion
I_{Nh} : Harmonic current generated by a non-linear portion

Figure 6.3 : Model for a linear and non-linear portion

On the basis of this observation, this dissertation classifies the separation method into the following two categories: a) an addition method; and b) a subtraction method, as shown in Table 6.1.

Table 6.1 : Set of separation methods for background voltage distortion effects

Method	Formulation	Side
Addition	$\mathbf{I_M(j\omega_n) = E_I(j\omega_1) + I_B(jn\omega_1)}$	**Standard**
Subtraction	$\mathbf{E_I(j\omega_n) = I_M(jn\omega_1) - I_B(jn\omega_1)}$	**Measurement**

6.2.3 Addition Method

From the viewpoint of the standard side, the addition method shown in Table 6.1 clearly shows that the measured current can be obtained when the background current distortion is identified. The non-linear current generated by linear portion associated with the background voltage distortion causes a decrease in the harmonic voltages at all the other buses, such that the background harmonic current is beneficial.

Harmonic currents generated by a linear portion can be obtained when we know the background voltage distortion and the harmonic impedance of the linear portion.

With the definition of the linear portion, the current generated by the linear port can be obtained at all frequencies as

$$I_L(j\omega_n) = Y_C(jn\omega_1) \cdot V_B(jn\omega_1) \tag{6.2}$$

With the application of IEC 61000-3-6, the set of the background voltage distortion at each node can be calculated by injecting the solution set of the harmonic current emission limits into all nodes where customers are connected. Substituting (6.2) into (6.1), the measured current can be rewritten as

$$I_M(j\omega_n) = -\left(E_I(jn\omega_1) + Y_C(jn\omega_1) \cdot V_B(jn\omega_1)\right) \tag{6.3}$$

This chapter focuses on the addition method with the application of IEC 61000-3-6.

6.2.4 Subtraction Method

In this section, this dissertation briefly presents the subtraction method. From the viewpoint of the measurement side, the subtraction method in Table 6.1 shows that the emission limits can be obtained by subtracting the unknown background harmonic current to the known measured current. Like the addition method, the emission limits can be obtained if the background harmonic current is identified. From the measured current and voltage, the fundamental impedance can be obtained as (6.4), based on the definition of the portion.

$$Y_C(j\omega_1) = \frac{I_M(j\omega_1)}{V_M(j\omega_1)} \tag{6.4}$$

Note that the current generated by a non-linear portion at the fundamental frequency is zero in accordance with the definition of a non-linear portion.

If we assume that the skin effect is neglected and the value of the resistance is not influenced by the frequency, and the load consists of the parameters R and L, then (6.4) can be expanded as

$$Y_C(j\omega_n) = \left|\frac{I_M(j\omega_1)}{V_M(j\omega_1)}\right|\left(\cos(\phi_1 - \theta_1) + jn\sin(\phi_1 - \theta_1)\right) \tag{6.5}$$

where θ_1, φ_1 are the phase angles of the voltage and current, respectively.

Substituting (6.5) into (6.2), the current generated by a linear portion I_L can be obtained as

$$I_L(j\omega_n) = \sum_{K=1}^{n} \left| \frac{I_M(j\omega_1)}{V_M(j\omega_1)} \right| \left(\frac{V_B(jK\omega_1)}{\sqrt{\cos(\theta_1 - \phi_1)^2 + K^2 \sin(\theta_1 - \phi_1)^2}} \right) \cdot \sin\left(K\omega t + \theta_K - \tan^{-1} K \frac{\sin(\theta_1 - \phi_1)}{\cos(\theta_1 - \phi_1)} \right) \tag{6.6}$$

Note that we assume that the equivalent circuit is considered to be a load with a predominantly inductive reactance. Although the important factor is that the current component should lag the voltage component at the fundamental frequency, the considerable installation of capacitors will call for changes, which are not considered in this dissertation.

6.2.5 Simple arithmetic result of the addition method

To demonstrate the effectiveness of the addition method, this dissertation carried out a simulation with a balanced three-phase system, as shown in Figure 6.4. The current injection method is adopted as an ideal current source model that is not affected by the background voltage distortion as a non-linear source representation. The major goal of the simulation is to investigate the trend of the THD of I_M, I_L and E_I at bus 2 when we generate the background voltage distortion at bus 2 by injecting a non-linear current into bus 3. The system parameters in Figure 6.4 are shown in Table 6.2.

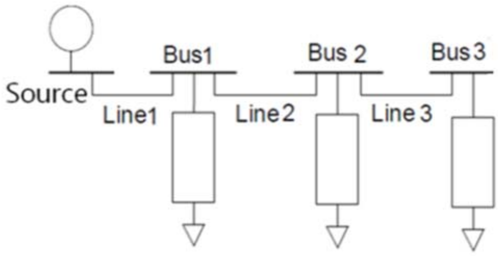


Figure 6.4 : Case-study model

The customer connected to Bus 2 in Figure 6.4 is under a compliance test, and the load is not changed. Even though the measured THD_{VM} on Bus 2 is changing, due to the change of the customer's harmonic current injection on Bus 3, the THDi of E_I generated by the customer side on Bus 2 should be constant.

Table 6.2 : Parameters for simulations

	Distribution Line Impedance[Ω]			Load Impedance[Ω] (per phase, wye)		
	Z_{Line1}	Z_{Line2}	Z_{Line3}	Z_{Load1}	Z_{Load2} No change	Z_{Load3} Change
Positive	0.1+j1.0	0.1+j1.0	0.1+j1.0	100+j20	100+j20 Three Phase Load[1)] (Six-Pulse Converter)	
Negative	0.1+j1.0	0.1+j1.0	0.1+j1.0			
Zero	0.2+j2.5	0.2+j2.5	0.2+j2.5			

1) A uniform probability-density function is used as phase angles.

The simulation results are shown in Figure 6.5. As expected, the levels of the background harmonic current I_B is increased, according to raising the level of the background voltage distortion level (THD_{VM}). I_B is changed with respect to the change of THD_{VM} on Bus 2. However, E_I has shown independence with respect to the change of THD_{VM} on Bus 2.

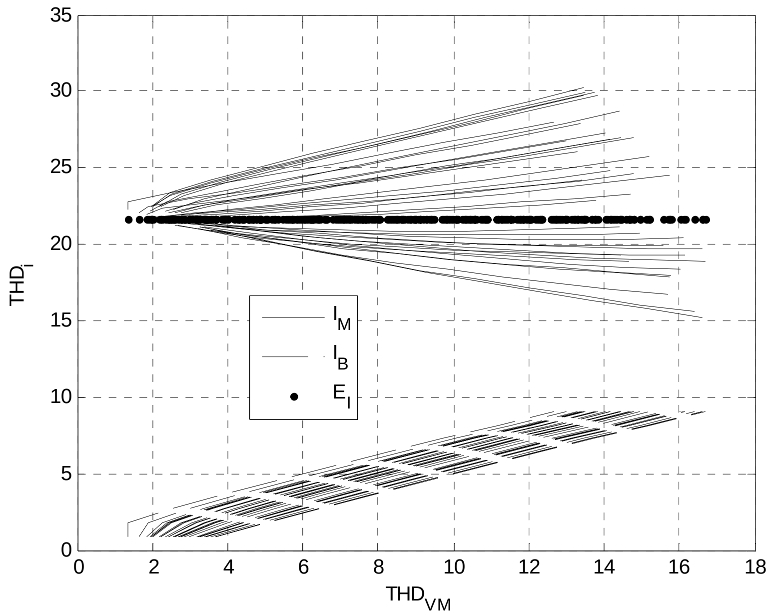


Figure 6.5 : Simulation results of I_M, I_B and E_I

6.3 Proposed method

The addition method clearly shows that the measured harmonic current at a POE can be separated if we know the background voltage distortion, load impedances, and the emission limits. To obtain the solution set of the background voltage distortion, the current emission limits should be allocated to all of the customers connected to a given distribution system. In this chapter, the current emission limits of all customers are evaluated in accordance with the principles of IEC 61000-3-6. Then, the set of current emission limits are injected into the given system to identify the resulting voltage distortions at all of the nodes. The set of the resulting voltage distortion will be the background voltage distortions. Finally, to evaluate the current emission limits, according to IEC 61000-3-6, the principles of IEC 61000-3-6 are applied to the proposed method, such as the basic EMC concepts related to harmonic distortion, general principles for emission limits, the general summation law and the sharing method of the global harmonic voltage contribution. For simplicity, this dissertation does not treat the impact of the HV and LV systems, since the MV system is the focus of this dissertation. It is not the purpose of this dissertation to discuss the principles applied to the methods. More detailed explanations of these essential concepts can be found in [1]. The procedure for obtaining the background harmonic current is briefly shown in Figure 6.6.

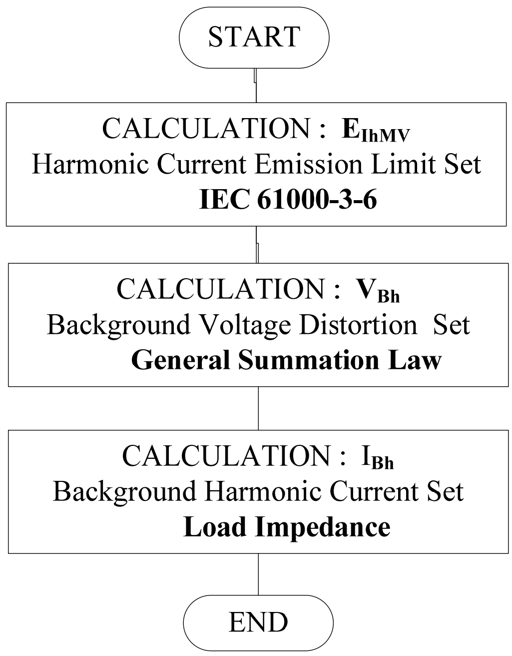


Figure 6.6 : Procedures for evaluating the background harmonic current

6.3.1 Background Voltage Distortion

To calculate the propagation of harmonic currents with the current injection method, the system impedance matrix is needed. Traditionally, the network relationship can be represented by an admittance or impedance matrix. This dissertation uses the system impedance matrix instead of the admittance matrix in order to avoid the time-consuming inversion of the matrix.

$$[\mathbf{V_{Bh}}] = [\mathbf{Y_h}]^{-1} \cdot [\mathbf{E_{Ih}}] = [\mathbf{Z_h}] \cdot [\mathbf{E_{Ih}}] \tag{6.7}$$

where $[V_{Bh}]$ is the vector of the unknown harmonic voltage distortion, [Zh] is the harmonic impedance matrix, and $[E_{Ih}]$ is the vector of the harmonic current emission limits.

When many customers producing harmonic currents are present in the same distribution system, the harmonic current in the lines and the harmonic voltage at the point of evaluation (POE) depends on the superposition effect caused by different amplitudes and phase angles of the currents emitted from different sources. An exact evaluation of resulting harmonic voltages (vectorial sum) is restricted to a few special cases. Taking the algebraic sum of the contributions by each harmonic source may represent the worst case, but this method often leads to unrealistically high values, especially at high harmonic orders. IEC 61000-3-6 treats harmonics as stochastic quantities. This contrasts with the present version of IEEE Std. 519, in which harmonics are considered as deterministic [17]. Therefore, the summation problem arises when studying the connection of a new customer load producing harmonics. The lack of information, and the inherent variability concerning all of the individual loads, which generate harmonics, leads to the necessity of using a statistical approach for evaluating the resulting harmonic vectors. In such an approach, each harmonic source is represented by a randomly time-varying vector. Both the magnitude and phase angle of these vectors are modeled by the means of distribution laws.

Two summation laws for evaluating the summation of a number of harmonic sources are introduced in IEC 61000-3-6 [73]. The first summation law [1, 34, 83] is a simple linear law making use of diversity factors. The approach using diversity factors may be especially useful with the phase angles of the already existing (background) harmonics. The second method[1, 34, 83] is developed, based on the Monte-Carlo approach, considering that the compatibility level has to be met with a probability of 95% or better [35]. The second summation law (referred to as the general summation law) is more general and combines the harmonic contributions from the non-linear loads; thus, it is considered as more applicable in most circumstances, since it does not consider the load types. IEC 61000-3-6 recommends the general summation law for voltages and currents A in Equation (4.1).

The stochastic treatment has two distinctive advantages over a deterministic approach. Firstly, it allows time and phase diversity between harmonic sources to be accounted for in a relatively simple manner by representing harmonic voltages and currents as 95% non-exceeding quantities. Secondly, the stochastic treatments eliminate the need for the phase angle of harmonic voltage and current sources.

With the application of Equation (4.1), the set of the background voltage distortion can be rewritten as

$$[\mathbf{V_{Bh}}] = \left([\mathbf{Z_h}]^{*\alpha} \cdot [\mathbf{E_{Ih}}]^{*\alpha}\right)^{*\frac{1}{\alpha}} \tag{6.8a}$$

For a system with the “n” node, the expanded form of (6.8a) is expressed as

$$\begin{bmatrix} V_{Bh,1} \\ V_{Bh,2} \\ \vdots \\ V_{Bh,n} \end{bmatrix} = \left(\begin{bmatrix} Z_{h,11} & Z_{h,12} & \cdots & Z_{h,1n} \\ Z_{h,21} & Z_{h,22} & \cdots & Z_{h,2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{h,n1} & Z_{h,n2} & \cdots & Z_{h,nn} \end{bmatrix}^{*\alpha} \cdot \begin{bmatrix} E_{Ih,1} \\ E_{Ih,2} \\ \vdots \\ E_{Ih,n} \end{bmatrix}^{*\alpha} \right)^{*\frac{1}{\alpha}} \tag{6.8b}$$

Equation (6.8) simply shows that the set of the resulting voltages is the result of the different harmonic currents participating, based on the superposition principle.

6.3.2 Background Harmonic Current

Once the solution set of the background voltage distortion has been achieved, the background harmonic current can be evaluated with the harmonic impedance of the customer's installation in accordance with Equation (6.2). Regarding the harmonic impedance, the linear portion generating the fundamental current can be identified, based on the given agreed power of the customer with the assumption of a specific power factor.

The consumer's loads play a very important part in obtaining the background harmonic current. Computer simulations have indicated that the addition of loads can result in either an increase or decrease in the harmonic flow [17]. Although there are several proposed linear models, it is difficult to establish a model, based on theoretical analysis. Therefore, utilities should be encouraged to develop a data basis of their geographic electric regions with as much information as possible on the composition of the load and power factor correction elements.

To intuitively demonstrate the proposed method, the example B.2.3 in [1] was chosen as a case study. All given conditions are exactly the same, except for the simplifying assumption of the uniformly distributed loads. For simplicity, this dissertation uses the simple parallel and serial RL with the power factor of 0.9 in this chapter.

The aim is the following: a) determining the 5th harmonic current emission limits in accordance with IEC 61000-3-6; b) determining the background voltage distortion; and c) determining the background harmonic current for a 500 kVA installation connected half-way along feeder No. 4, where the short-circuit power is 47 MVA at POE_{13}, as shown in Figure 6.7. The load impedance is 23.05p.u and 4.72pu with the parallel and serial models, respectively.

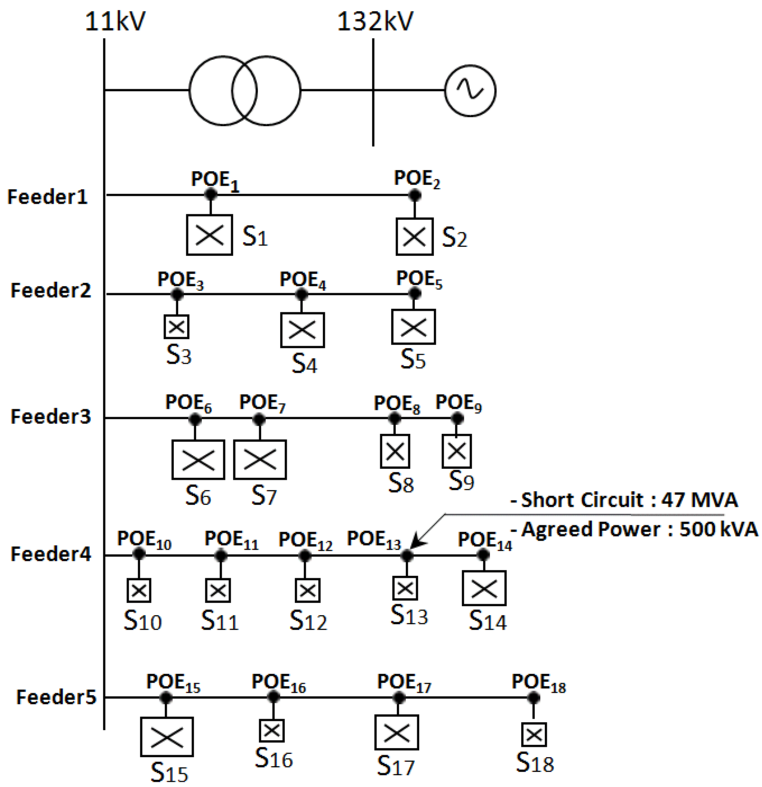


Figure 6.7 : Example of a distribution system showing an MV transformer and 5 feeders

Table 6.3 shows that the background voltage distortion and the harmonic current emission limit at POE_{13} are 2.82% and 6.97%, respectively. The background harmonic current is 0.24% and 1.2% with respect to the parallel and serial models, respectively. These results obviously show that the level of the background harmonic current depends on the level of the background voltage distortion and the load model of the customer. From the viewpoint of the background voltage distortion level, the customer at the worst voltage distortion can inject the most background harmonic current.

Table 6.3 : Test results for the justification of IEC 61000-3-6

Feeder NO.	PCC Node NO.	Load (MVA)	SC (MVA)	V_{Bh}	E_{Ih} 1)	R//L			R-L		
						Z	I_{Bh}	I_{Mh}	Z	I_{Bh}	I_{Mh}
1	1	2.5	120	2.56	7.03	4.61	0.22	6.81	0.94	1.09	5.94
	2	1.5	47	2.82	5.09	7.68	0.24	4.85	1.57	1.20	3.89
2	3	1.0	130	2.52	7.80	5.76	0.22	7.58	1.18	1.07	6.73
	4	1.5	70	2.72	5.99	6.78	0.24	5.76	1.39	1.15	4.84
	5	1.5	47	2.75	8.06	38.41	0.24	7.82	7.86	1.17	6.89
3	6	1.5	130	2.49	8.09	5.76	0.22	7.88	1.18	1.06	7.04
	7	1.5	110	2.52	8.46	7.68	0.22	8.25	1.57	1.07	7.40
	8	1.0	60	2.75	6.53	16.46	0.24	6.29	3.37	1.16	5.36
	9	1.0	37	2.82	5.40	14.41	0.24	5.16	2.95	1.20	4.21
4	10	1.0	140	2.50	7.59	4.61	0.22	7.38	0.94	1.06	6.53
	11	1.0	110	2.52	9.50	11.52	0.22	9.29	2.36	1.07	8.43
	12	1.0	80	2.67	7.46	11.52	0.23	7.22	2.36	1.13	6.32
	13	0.5	47	2.82	6.97	23.05	0.24	6.72	4.72	1.20	5.77
	14	2.5	28	2.99	4.41	11.52	0.26	4.15	2.36	1.27	3.14
5	15	1.5	130	2.47	12.02	23.05	0.21	11.81	4.72	1.05	10.98
	16	1.0	90	2.94	7.19	23.05	0.25	6.93	4.72	1.25	5.94
	17	1.5	60	3.70	4.17	11.52	0.32	3.85	2.36	1.57	2.60
	18	1.0	20	4.00	2.72	3.84	0.35	2.38	0.79	1.70	1.03
GhMV : 4%, Fault level at the sending end: 150MVA											
pf=0.9											

1) There are discrepancies compared to the solution of IEC 61000-3-6, since this dissertation calculates the current emission limits without the simplifying assumption of the uniformly distributed load, which is used in IEC 6000-3-6.

Regarding the non-linear current, "harmful" and "useful" harmonic currents are introduced in [17]. In a simple, but logical statement, it can be claimed that if the injection of a harmonic current at a certain bus causes a decrease in the harmonic voltages at all other buses, such a harmonic current is beneficial. At a first glance, we can assume that if a non-linear portion generates harmonic power, the current harmonics injected are detrimental, but if a load (linear or non-linear portion) receives harmonic power in accordance with its own impedance, it helps reduce the voltage distortion at its own bus or elsewhere [3-9]. To help clarify the cause-effect mechanism produced by "offending" and "friendly" harmonic currents, a few basic examples are presented in [17]. Therefore, the background harmonic current is beneficial to the customers having non-linear loads under the compliance assessment. In other words, the customer at the worst node is the best beneficiary from the background voltage distortion. This result is fair to customers, since IEC 61000-3-6 penalizes consumers connected far away on the line, at the short-circuit level. The background voltage distortion compensates for this penalty.

6.4 General Application

To generally demonstrate the feasibility of the proposed method, the IEEE 123 bus test system [79] is selected to show the features of the proposed method with an arbitrary network system, such as a radial and meshed system in accordance with the principles in [1]. For test purposes, three loops are added to the test system, as shown in Figure 6.8. The tie lines between buses 11 and 33, buses 39 and 66, and buses 107 and 114 are tied.

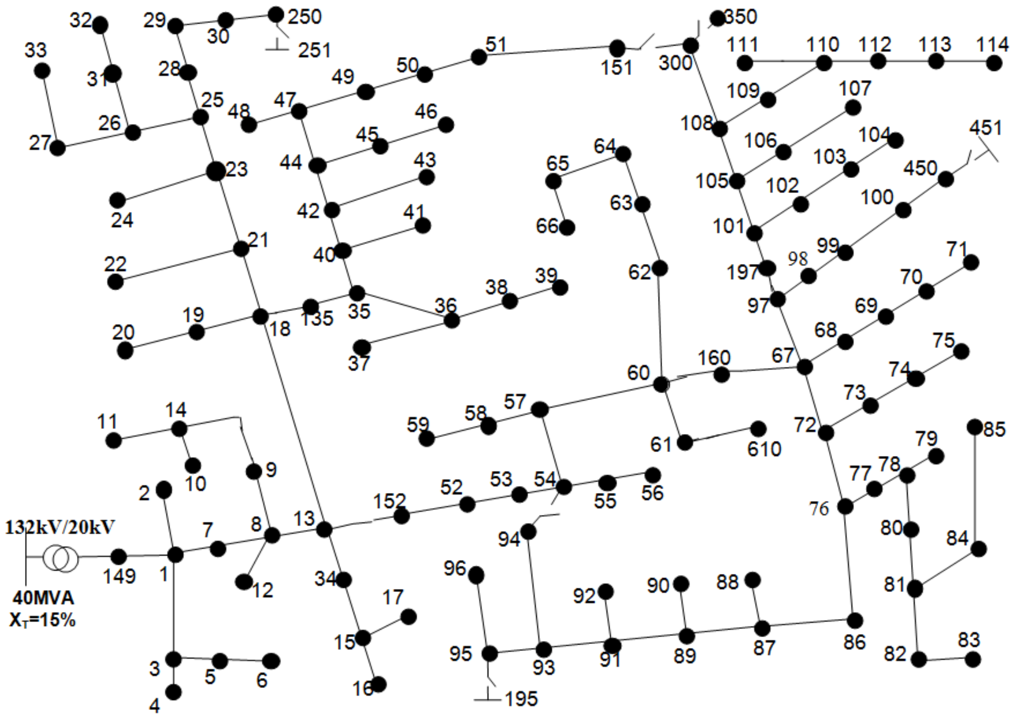


Figure 6.8 : IEEE 123 bus system

The results in Table 6.4 are consistent with the test result of IEC 61000-3-6. Table 6.4 clearly shows that the level of background harmonic current depends on the level of the background voltage distortion.

Table 6.4 : Test results of the IEEE 123-bus system

Node	Load (MVA)	SC (MVA)	**Zpu (R//L)**	Harmonic Allocation Limit %[1)]							
				Radial				Meshed			
				V_{Bh}	E_{Ih}	I_{Bh}	I_M	V_{Bh}	E_{Ih}	I_{Bh}	I_M
2	0.50	181	921.96	1.81	10.19	0.16	10.04	2.17	10.91	0.19	10.73
4	0.50	157	921.96	1.82	9.49	0.16	9.33	2.18	10.16	0.19	9.97
6	0.50	133	921.96	1.83	8.73	0.16	8.57	2.19	9.35	0.19	9.16
10	1.00	108	460.98	2.41	6.44	0.21	6.24	2.99	7.03	0.26	6.77
11	1.50	108	307.32	2.41	5.74	0.21	5.53	3.04	6.38	0.26	6.11
12	1.50	139	307.32	2.35	6.51	0.20	6.31	2.82	6.98	0.24	6.73
16	1.00	107	460.98	2.63	6.42	0.23	6.19	3.18	6.92	0.28	6.64
17	1.00	108	460.98	2.63	6.44	0.23	6.22	3.27	7.02	0.28	6.74
20	0.50	85	921.96	2.85	6.98	0.25	6.74	3.29	7.94	0.29	7.66
22	0.50	80	921.96	2.87	6.77	0.25	6.52	3.26	7.85	0.28	7.57
24	0.50	75	921.96	2.89	6.55	0.25	6.30	3.24	7.74	0.28	7.46
32	0.50	66	921.96	2.91	6.14	0.25	5.89	3.16	7.73	0.27	7.46
33	0.50	63	921.96	2.92	5.99	0.25	5.74	3.04	8.73	0.26	8.47
37	1.00	71	460.98	2.97	5.24	0.26	4.98	3.49	6.77	0.30	6.47
39	1.00	67	460.98	2.98	5.09	0.26	4.83	3.56	6.48	0.31	6.17
41	1.00	77	460.98	2.97	5.47	0.26	5.21	3.45	6.34	0.30	6.04
43	1.00	70	460.98	3.01	5.21	0.26	4.95	3.49	6.00	0.30	5.69
46	1.00	67	460.98	3.03	5.10	0.26	4.84	3.51	5.85	0.30	5.55
48	1.00	69	460.98	3.03	5.15	0.26	4.89	3.51	5.92	0.30	5.62
56	1.50	88	307.32	3.03	5.19	0.26	4.93	3.37	5.75	0.29	5.46
59	1.50	81	307.32	3.20	4.99	0.28	4.71	3.49	6.03	0.30	5.73
66	1.50	56	307.32	3.60	4.15	0.31	3.84	3.56	5.77	0.31	5.46
71	1.00	57	460.98	3.71	4.70	0.32	4.38	3.74	5.64	0.32	5.32
75	1.00	55	460.98	3.76	4.61	0.33	4.29	3.73	5.62	0.32	5.29
79	1.00	56	460.98	3.80	4.65	0.33	4.32	3.74	5.78	0.32	5.45
83	1.00	46	460.98	3.86	4.23	0.33	3.89	3.80	5.10	0.33	4.77
85	1.00	42	460.98	3.88	4.04	0.34	3.71	3.82	4.82	0.33	4.49
88	0.50	51	921.96	3.86	5.40	0.34	5.06	3.52	7.58	0.31	7.28
90	0.50	48	921.96	3.89	5.27	0.34	4.93	3.48	7.62	0.30	7.32
92	0.50	46	921.96	3.90	5.15	0.34	4.81	3.44	7.64	0.30	7.34
94	1.50	45	307.32	3.92	3.71	0.34	3.37	3.41	5.69	0.30	5.40
96	0.50	44	921.96	3.92	5.00	0.34	4.66	3.27	8.56	0.28	8.27
104	1.00	51	460.98	3.81	4.45	0.33	4.11	3.86	5.26	0.34	4.93
107	1.00	53	460.98	3.85	4.51	0.33	4.17	3.96	5.48	0.34	5.13
111	2.00	46	230.49	3.98	3.47	0.35	3.12	4.00	4.21	0.35	3.86
114	2.00	44	230.49	4.00	3.37	0.35	3.02	3.96	4.49	0.34	4.15
151	1.00	61	460.98	3.05	4.85	0.26	4.59	3.53	5.53	0.31	5.22
250	0.50	63	921.96	2.91	6.03	0.25	5.78	3.22	7.21	0.28	6.93
300	2.00	49	230.49	3.93	3.55	0.34	3.21	3.98	4.19	0.35	3.85
610	1.50	68	307.32	3.56	4.55	0.31	4.25	3.65	5.45	0.32	5.14
GhMV : 4%, Fault side at bus 149 : 267MVA, Line : 0.6504 ohms/mile											
Linked switch sets : 11-33, 39-66, 107-114											
Distributed Generator (DG) : DG1-33, DG2-114, DG3-83											

1) % of the load current of each single user of agreed power.

2) In this case, the given line length has been increased 10 times, since some long MV feeders can have short-circuit powers that vary by 10:1 or more from the supply to the far end.

6.5 Conclusions

A new approach has been introduced to identify the background harmonic current caused by the background voltage distortion with IEC 61000-3-6. Firstly, this chapter introduced a simple, but intuitive basic concept of “a linear and non-linear portion” for separating the effects of background voltage distortion from customer harmonic contributions.

To calculate the background voltage distortions in a given system by injecting the set of harmonic current emission limits evaluated by IEC 61000-3-6, this dissertation proposed a new method of harmonic flow, based on the general summation law, without any simplifying assumption.

Additionally, with the application of the concept, “linear and non-linear portion,” this dissertation clearly demonstrated how to evaluate the background harmonic current from background voltage distortions.

Finally, the feasibility of the proposed methods are clearly demonstrated with a simple example in IEC 61000-3-6 and the application of the IEEE 123 network topologies.

This dissertation strongly supports IEC 61000-3-6 and adds to its value. In addition, the findings of this dissertation could help users determine the harmonic contributions of the parties involved more reasonably, accurately and efficiently with the application of distribution automation systems (DAS).

CHAPTER 7

Conclusions and Contributions

This chapter provides the conclusions and contributions of this dissertation. This is followed by a list of the publications produced thus far in connection with this research.

7.1 Conclusions

Although IEC 61000-3-6 and IEEE Std. 519 standards provide guidelines for allocating the harmonic emission limits that divide the responsibility between the utility and the customer, disputes may arise regarding the different solution sets of the emission limits since the planning levels, the voltage and current emission limits are designed differently.

IEC 61000-3-6 has rationales regarding its own principles and has detailed formula for the emission limits, but an assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. Additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with large number of branches and buses in the MV system.

IEEE 519 can be considered as simpler of the two standards because the allowable current injection levels are pre-calculated, albeit with insufficient investigation for its emission limits. An inconsistency permits the allowed current limits to boost voltage distortion limits beyond acceptable threshold theoretically.

This dissertation specifically addresses the improved harmonic allocation methods according to the principles of IEC 61000-3-6 and IEEE Std. 519 for the MV and HV-EHV customers.

Chapter 1 presents a detailed literature survey to summarize the state of the art techniques that are pertinent to the methods proposed in this research.

Chapter 2 provides a practical method to allocate harmonic emission limits in accordance with the principles of IEC 61000-3-6. IEC 61000-3-6 presents a simple method with a simplifying assumption for allocating harmonic current emission limits to MV systems. Although this simple method has contributed to calculating emission limits with handwritten calculations, an assumption of uniformly spatially distributed loads (useful for simplification) often leads the solution set to inaccuracy. An additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with a large number of branches and meshed systems. A new method has been developed with the application of the influence coefficient in to improve those shortcomings. This is a new attempt to implement an algorithm for an evaluation of exact harmonic allocations in complex network topologies with wide-ranging resistances and reactances (such as radial, weakly meshed or distributed generation systems without any simplifying assumptions).

Chapter 3 compares the harmonic allocation methodologies of both IEC 61000-3-6 and IEEE Std. 519. Assessing, comparing and contrasting the harmonic allocation methodologies of both IEC 61000-3-6 and IEEE Std. 519 in the MV systems have been carried out with analytical proofs to analyze the validity of the principles applied to both standards. The ultimate goal of harmonic standards is to fairly allocate harmonic emission limits to each customer to keep a specific voltage level in a given system. However, both standards differently approach the issue of allocating emission limits. Therefore, the solution sets derived from each of these different approaches are not identical. On the surface, it looks as though they complement each other. However, an in-depth analysis shows some significant differences. It is impossible to directly compare both standards, since they are developed based on different methodologies. Therefore, the comparison is carried out with the key question of whether or not both solution sets ultimately arrive at the same conclusion. Significant differences between both standards have been clearly shown in the planning levels, the voltage emission limits and the current emission limits, and some hidden problems of IEEE Std. 519 have been also revealed with analytical proofs and simulations.

Chapter 4 proposes how to apply the stochastic method to IEEE Std. 519 and three correction factors to improve the harmonic current emission limits of IEEE Std. 519 in MV systems. IEEE Std. 519 takes the simple deterministic method, which often leads to unrealistically high values, especially at high harmonic orders. Moreover, due to the cost of being simple and universal pre-calculated harmonic current emission limits, IEEE Std. 519 cannot fully consider the precarious nature of distribution systems in its own emission limits. Therefore, the emission limits of IEEE Std. 519 often boost voltage distortions theoretically up to twice beyond planning levels. This dissertation proposes the necessity to apply the stochastic method in IEC 61000-3-6 to IEEE Std. 519, and show the results of IEEE Std. 519 emission limits, based on the stochastic harmonic flow. In addition, three correction factors are developed to compensate for the influences of the following uncertainties of distribution systems on the harmonic current emission limits:

the variation of the main transformer size (referred to as supply capacity here), the number of feeders, and system voltage levels. The feasibility of the correction factors proposed is obviously proven, based on a multi-feeder model of distribution systems with the Monte-Carlo method.

Chapter 5 proposes a methodology for sharing the common HV-EHV planning levels between the different substations or busbars in the supply system (referred to as a global contribution) in accordance with the principles of IEC 61000-3-6. IEC 61000-3-6 is composed of two quite different sets of principles for allocating harmonic emission limits in MV and HV-EHV systems, respectively. The ultimate goal of IEC 61000-3-6 for HV-EHV systems is to fairly apportion maximum global contribution limits to considered stations under the consideration of the ratio of the power supply to the total power supply capacity of the given system while guaranteeing the planning levels. In this chapter, this dissertation analytically investigates the allocation method of the global contribution in IEC 61000-3-6. From the analysis results, this dissertation clearly proves that the major principles applied to IEC 61000-3-6 have problems that should not be ignored, since the solution set often violates the planning level. To overcome these problems, this dissertation proposes a new method that fairly apportions the global contribution limit to each busbar while guaranteeing the planning levels in HV-EHV systems. The feasibility of the proposed method has been clearly demonstrated by guaranteeing that the worst resulting voltage distortions derived from the proposed method are equal to the given planning level, regardless of system structures and circumstances.

Chapter 6 proposes a methodology to identify the effects of the background voltage distortion on a particular MV customer under a harmonic compliance test in accordance with the IEC 61000-3-6 principles. IEC 61000-3-6 and IEEE Std. 519 are the harmonic standards that are developed to fairly allocate emission limits to their customers so as not to violate given planning levels without consideration of the background voltage distortion. Therefore, one major difficulty in harmonic standards is how to separate the customer and supply side harmonic contributions from the measured quantity. Customers under compliance tests are often concerned about the effects of background voltage distortions generated by the other customers at the point of evaluation (POE). To solve this problem, separation methods have been proposed from the viewpoint of the measurement side. This dissertation is the first attempt to approach this problem from the viewpoint of harmonic standards. This dissertation clearly proposes a concrete method of separating contributions generated by a particular customer from other customers connected to the supply system, based on IEC 61000-3-6. In addition, this dissertation clearly concludes that the impact of background voltage distortion cannot be ignored, since a considerable non-linear current can be generated in accordance with the level of the load impedance and the background voltage distortion at the POE.

All the proposed methods in this dissertation strongly supports IEC 61000-3-6 and IEEE Std. 519 and adds to its value, and could help the users to allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently with application of the distribution automation systems (DAS). This dissertation will be to serve as a stepping stone to improve the emission limits of both standards.

7.2 Contributions

This dissertation will yield the following contributions:

- **Task I**

  The harmonic allocation method of IEC 61000-3-6 for MV customers often leads the solution set to inaccuracy because of the assumption of uniformly spatially distributed loads (useful for simplification). Additional problem is the difficulty in implementing the allocation method of IEC 61000-3-6 to the real distribution systems with large number of branches and meshed systems. To improve those shortcomings in IEC 61000-3-6, the proposed method has been developed.

  - A method developed for evaluating harmonic allocations in complex network topologies with wide-ranging resistances and reactances (such as radial, weakly meshed or distributed generation systems without any simplifying assumptions).
  - The method strongly supports IEC 61000-3-6 and adds to its value, and could help the utilities to allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently with application of distribution automation systems (DAS).

- **Task 2**

  Comparative analysis of current harmonic emission standards (IEC 61000-3-6 and IEEE Std. 519) in MV systems have been carried out in detail to investigate the weak and strong points of both standards since both standards approach the issue of allocating the emission limits differently, and the solution set derived from both are not identical. On the surface, they complement each other. However, an in-depth analysis has shown some significant differences. Analysis has been carried out with the primary goal of whether or not the harmonic standards make the systems inviolable if all customers are in compliance with the guidelines. From the results of the analysis, this dissertation has clearly shown a significant difference, inconsistency and inaccuracy of both standards. Comparison has been performed with the key question of whether or not both solution sets ultimately arrive at the same conclusion.

- Demonstrating significant differences between IEC 61000-3-6 and IEEE Std. 519 through in-depth comparisons with the following viewpoints: a) planning levels, b) harmonic voltage emission limits, and c) harmonic current emission limits.
- Large discrepancies (up to over 200%) of the harmonic current emission limits evaluated by both standards have been clearly shown from the results of simulations on the IEEE 123 system modified to cover the various distribution network characteristics (i.e., radial, meshed, distributed generator, and meshed with distributed generator systems).
- This dissertation has obviously shown that IEEE Std. 519 has a problem not to fulfill the planning levels since it does not have a function to control the system harmonic absorption capacity, and violate the planning level up to 400% in the given example.

- Demonstrating the inaccuracy problem of an allocation constant (A_{hMV}), which is introduced in IEC 61000-3-6 with simplifying assumptions to allocate the harmonic current emission limits under the consideration of the multi-feeder distribution systems. Inaccuracy of IEC 61000-3-6 is 7.41% in the given example.

o **Task 3**

IEEE Std. 519 takes the simple deterministic method, which often leads to unrealistically high values, especially at high harmonic orders. Moreover, due to the cost of being simple and universal pre-calculated harmonic current emission limits, IEEE Std. 519 cannot fully consider the precarious nature of distribution systems in its own emission limits. Therefore, the emission limits of IEEE Std. 519 often boost voltage distortions theoretically up to twice beyond planning levels. Moreover, at the expense of simplicity, it is impossible for IEEE Std. 519 to fully consider the following random nature of distribution systems: a) supply capacities; b) the number of feeders; and c) system voltage levels. To include the influence of the uncertainties on the emission limits of IEEE Std. 519, this dissertation proposes three correction factors: the supply capacity, the multi-feeder and the system voltage.

- Presenting how to apply the stochastic method to IEEE Std. 519 and three correction factors to improve the harmonic current emission limits of IEEE Std. 519 in MV systems.
- Proposing the necessity that IEEE Std. 519 should adopt the stochastic method in IEC 61000-3-6 instead of the deterministic method and clearly demostrating that IEEE Std. 519 yields very improved results through the general summation law, which is developed based on the Monte-Carlo approach, considering that the compatibility level has to be met with a probability of 95% or better.
- Proving the universal pre-calculated harmonic current emission limits might lead IEEE Std. 519 to boost voltage distortions theoretically up to twice beyond the planning levels, since it does not fully consider the precarious nature of distribution systems.
- Proposing three correction factors under consideration of influences of the random nature of distribution systems on the emission limits of IEEE Std. 519.

o **Task 4**

The harmonic emission allocation methods in IEC 61000-3-6 are composed of two quite different principles for MV and HV (HV-EHV) systems. For HV systems, the major principle is how to share planning levels and allocate maximum global contribution limits in meshed systems with the application of the influence coefficient. This dissertation has clearly proved that the allocation principle in IEC 61000-3-6 has some hidden problems that should not be ignored, which are due to invalid use of the influence coefficient. These problems associated with the major principle are investigated based on the case studies and numerical analysis. To correct these problems, this dissertation proposes a new exact methodology for sharing harmonic planning levels and allocating emission limits without any inaccuracy. Moreover, the proposed method solves the resonance situation without modifying the influence coefficients. Finally, the effectiveness of the proposed method has been clearly investigated by investigating whether the worst value among the solution sets of the resulting voltage distortion guarantees not to violate the planning levels. The proposed method strongly supports the utilities to allocate harmonic emission limits to their own customers more reasonably, accurately and efficiently.

- Demonstrating the following hidden problems in IEC 61000-3-6 for HV-EHV customers: a) invalid definitions of the relationship between the planning levels in HV-EHV systems and the individual emission limits, b) invalid applications of the influence coefficients between the different substations or busbars in case meshed systems.
- Proposing a new exact methodology for sharing harmonic planning levels in meshed HV-EHV systems with following concepts: a) a reference harmonic voltage set, b) a reference harmonic current set, c) a reference harmonic global contribution set, and d) an allocation

constant. The feasibility of the proposed method has been demonstrated by demonstrating an accuracy and efficiency with and without the resonance condition in the example system.

- **Task 5**

  IEC 61000-3-6 and IEEE Std. 519 are the harmonic standards that are developed to fairly allocate emission limits to their customers so as not to violate given planning levels without consideration of the background voltage distortion. Therefore, one major difficulty in harmonic standards is how to separate the customer and supply side harmonic contributions from the measured quantity. Customers under compliance tests are often concerned about the effects of background voltage distortions generated by the other customers at the point of evaluation (POE). To solve this problem, separation methods have been proposed from the viewpoint of the measurement side. This is the first attempt to approach this problem from the viewpoint of harmonic standards.

- Developing a new method to identify the background harmonic current caused by the background voltage distortion with IEC 61000-3-6.
- Introducing a simple, but intuitive basic concept of "a linear and non-linear portion" for separating the effects of background voltage distortion from customer harmonic contributions.
- Proposing a new method of harmonic flow, based on the general summation law, without any simplifying assumption to calculate the background voltage distortions in a given system by injecting the set of harmonic current emission limits evaluated by IEC 61000-3-6.

7.3 Publications

- Namhun Cho and Miroslave M Begovic; "Allocation of Individual Harmonic Emission Limits to MV Customers in Accordance with the Principles of IEC/TR 61000-3-6," IEEE Transactions on Power Delivery, Submitted Jan. 2012.

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